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NEUTRINO PHYSICS: AN OVERVIEW

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1 Introduction

Neutrino Physics is one of the fastest evolving fields in physics today. Among the early experiments that detected neutrinos in the laboratory was the underground cosmic ray experiment located in a mine in the Kolar Gold Fields (KGF). After measuring the cosmic ray flux at successive depths underground, the experimenters noted that at sufficiently great depths of over 2000 ms, the cosmic rays were almost completely absorbed during their travel through the Earth. At such depths, events from neutrino interactions in the detector or the surrounding rock could be observed, cleanly, with very little background from cosmic ray events. These neutrinos are the so-called atmospheric neutrinos, since they are produced in the interaction of cosmic rays with Earth's atmosphere. This detection of atmospheric neutrinos was in 1965. The closure of the KGF mines more than a decade ago inevitably led to a decline in India-based experiments related to neutrino physics. A historical perspective on experimental neutrino physics, including the KGF experiment in India, can be found in the article by **V.S. Narasimham** in this volume.

Subsequently, many other experiments around the world detected atmospheric neutrinos as well as neutrinos from other sources, including the Sun. Consistently, the results of these experiments disagreed with theoretical expectations in a manner that indicated the existence of some new physics related to neutrinos.

While neutrinos are considered to be massless particles within the Standard Model (SM) of particle physics, it is now believed that the bulk of the data on neutrinos and their interactions can be explained by assigning masses to them. This discovery of neutrino mass has come indirectly from the discovery of *neutrino oscillations*. Neutrinos have thus provided the first evidence for new physics beyond the SM. Hence there is tremendous interest in studying neutrinos using different sources and detectors, in order to pin down the various properties of these particles.

This world-wide excitement in the field has led to a clearly defined interest within the Indian community to revive neutrino experiments in India. Currently, a feasibility study for an India-based Neutrino Observatory (INO) is in progress. For more details on this, see the article by **N.K. Mondal** in this volume. The neutrino community has expanded to include the expertise of nuclear physicists, engineers, and electronics and soft-ware experts. The need was felt to have a pedagogic introduction to the vast field of neutrino physics where the current status of experiments and related phenomenology and theory would be summarised. It would thus be a handy reference for those interested in joining the project. This volume on neutrino physics is an attempt in that direction.

Detailed reviews of the exciting discoveries and developments in the field of neutrino physics are provided in the following articles in this volume. While the choice of topics does reflect to some extent the prejudices of the Editors, we have tried to provide as global and comprehensive a set of articles as possible.

In this particular article, we present an overview of the whole field of neutrino physics and at the same time provide the necessary connecting links by introducing the various other articles in the volume. Some interesting topics that could not be covered in the other articles are reviewed in some detail in this introductory article. The novel area of geoneutrinos is one of them.

2 Neutrinos: Some Facts

Neutrinos were first postulated by Pauli in 1930 to explain the continuous electron energy distribution in nuclear beta decay. Later, in 1934, they were christened as such by Fermi who made them the basis of his theory of weak interactions. Very early on, it was clear that these particles would be difficult to observe because their cross sections are so small. But in a series of experiments, Reines and Cowan conclusively proved their existence through the observation of the inverse beta decay process of the interaction of (anti)electron neutrinos from reactors with protons in the detector: $\overline{\nu}_e + p \to e^+ + n$. Apart from *electron neutrinos* which figure in nuclear beta decay, the separate identity of *muon neutrinos* was proved in 1962 and the discovery of the τ lepton a decade later implied the existence of the third neutrino, the *tau neutrino*, ν_τ. It was only in the year 2001 that its existence was proved by direct observation. A result of fundamental importance to neutrino physics is the precise measurement of the decay width of the Z-boson which implies the existence of three active neutrino flavours.

Neutrinos are produced both naturally and in the laboratory. Each of these sources provides information, sometimes overlapping, that is extremely important in understanding the intrinsic properties of the neutrinos. The energy spectrum of naturally produced neutrinos starts from fractions of electron-volts and spans an impressive range. Fig. 1 shows the spectra of neutrinos from different sources as a function of their energies. Some of the spectra shown are based on observations while others, especially those at high energies, are based on model calculations. While no single detector can fathom the many decades in energy, the very fact that neutrinos are produced over such a wide energy range poses challenging problems in their detection and understanding.

We now go on to discuss the recent developments. We begin with the solar neutrino problem because of its historical importance and then take up the atmospheric and reactor neutrinos. All these can be consistently analysed in terms of mixing and oscillations among the three neutrino flavours, as briefly described in Section 6. We then discuss direct measurements of neutrino masses and neutrinos in astrophysics and cosmology. We end by discussing possible models of neutrino masses and mixing that may explain the currently available data.

3 Solar Neutrinos

The basic process of thermonuclear fusion in the Sun (and also in stars) may be summarised as

$$p + p + p + p \to {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}.$$

The energy released in the process accounts for the luminosity of the Sun. From this, the solar neutrino flux at the Earth is calculated to be 70 billion/cm^2/sec. Notice that only electron neutrinos are produced.

Although the total number of neutrinos emitted by the Sun can be easily calculated from the solar luminosity, their *energy spectrum*, which is crucial for their experimental detection, requires a detailed modelling of the Sun and a detailed knowledge of various thermo-nuclear fusion reactions. The Standard Model of the Sun (SSM) does precisely this. Such a knowledge of the neutrino energy spectrum is needed to understand the energy-dependent signals in neutrino detectors.

While the dominant low-energy neutrino flux is basically determined by the solar luminosity, the flux of the high-energy neutrinos (the so-called boron-neutrino flux) is very sensitive to the various physical processes in the Sun and hence is a crucial test of the SSM.

The pioneering experiment on solar neutrinos started by Davis and collaborators in the 1960s is based on the inverse beta decay process:

$$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^- .$$

This experiment was mainly sensitive to the high energy Boron neutrinos and, to a small extent, to the lower energy Beryllium neutrino flux. It was found that the number of neutrinos detected was only a third of the predicted number. Over the three decades of operation of Davis's experiment, this discrepancy has remained and has been known as the solar neutrino puzzle. This deficit was confirmed by other independent experiments, notably the real-time Kamiokande and Super-Kamiokande water Cerenkov experiments in Japan and the Gallium-based radiochemical experiments of SAGE, GALLEX and GNO. All these experiments are mostly sensitive to electron neutrinos. The extent of deficit varied between roughly half to one-third.

Recent data from the Canada-based SNO experiment has clearly demonstrated that electron neutrinos are depleted while the total flux of Boron neutrinos (as evidenced from a measurement of neutral current events) is close to the theoretical expectation. This result implies that neutrinos mix and oscillate between flavours on their way from the Sun to the Earth. The article by **Amitava Raychaudhuri** in this volume provides more details on the neutrino oscillation

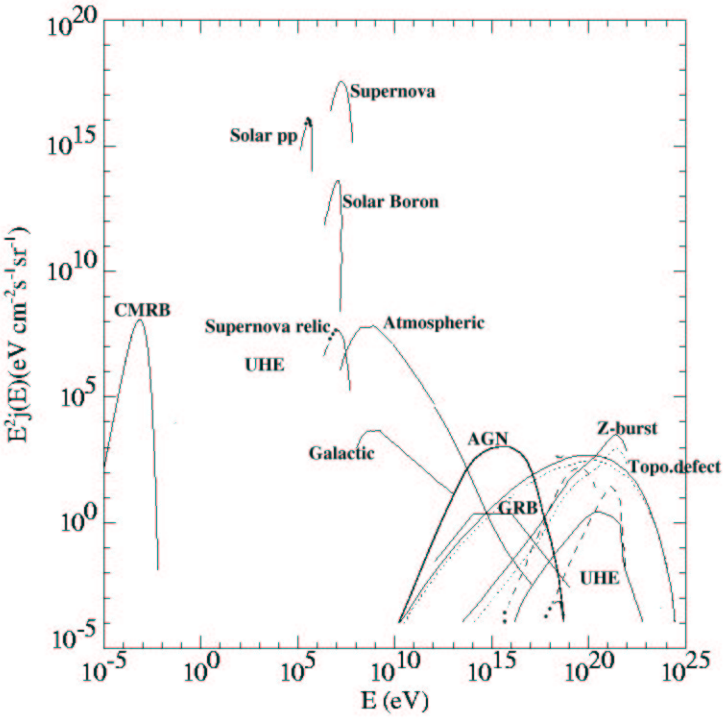

Fig. 1 Neutrino spectra from different sources as a function of energy. Figure taken from the talk presented by P. Bhattacharjee at the Neutrino-2001 meeting, Chennai, February 2001.

hypothesis and its application to the solar (and other) neutrino problems. See also the article by **S. Pakvasa** and **J.W.F. Valle** in this volume for a review on neutrino oscillations as well as non-standard solutions to the solar neutrino problem.

Thus, in one sweep the long-awaited SNO results have confirmed both the SSM and provided evidence for neutrino oscillations. We refer the interested reader to the article by **S. Goswami** in this volume for more details on solar neutrino detection and its impact on the neutrino oscillation hypothesis.

4 Atmospheric Neutrinos

Solar neutrinos carry MeVs of energy. We now shift to GeV neutrinos, of which atmospheric neutrinos are an example. As mentioned earlier, atmospheric neutrinos were first detected more than 35 years ago at the KGF mines, at depths where cosmic ray backgrounds were negligibly small. In succeeding decades, detailed studies of these atmospheric neutrinos were undertaken in many underground laboratories around the world.

Pions, formed during interaction of cosmic rays with Earth's atmosphere, decay into muons and mu type neutrinos. Subsequently these muons decay into an electron and two neutrinos one each of e and mu types. So in the neutrinos detected deep underground, for every e neutrino there must be two mu neutrinos. In other words, the ratio R of mu type to e type neutrinos must be roughly 2 (modulo variation due to cross-section). Observation of an electron (or a muon) signals the detection (via charged current (CC) interactions) of e (or mu) type neutrinos.

The Kamioka water Cerenkov detector in Japan detected electrons and muons from CC interactions of the corresponding neutrinos in water and measured the ratio R. While R was close to the theoretical expectation for the neutrinos coming downward, from the atmosphere above, it deviated considerably from it for the upward coming neutrinos that traverse the Earth and in fact was about half for those upward coming neutrinos that traversed an Earth diameter. Although the Kamioka detector and a few other detectors observed this anomaly in 1990, it required the Super-Kamioka detector with its superior statistics to establish the effect in 1998. It also determined that it is the muon neutrinos that are affected and not the electron neutrinos.

The explanation of this anomaly is again neutrino oscillation. Since the anomaly is in the *ratio* of the fluxes of two types of neutrinos, the inference of neutrino oscillation from the atmospheric neutrino anomaly is relatively free from the large uncertainties on the absolute flux. More details on the atmospheric neutrino problem are available in the articles by **S. Dugad** and **A. Raychaudhuri** in this volume.

5 Reactor Neutrinos

A fission reactor is a copious source of electron antineutrinos $\bar{\nu}_e$. The very first experimental detection of neutrinos was in fact made with reactor neutrinos. Fermi's theory of beta decay which was based on the existence of the neutrino was in such beautiful agreement with experimental data on the beta decays of nuclei that hardly anybody doubted the existence of neutrinos. Nevertheless Cowan and Reines realised the importance of directly detecting the antineutrinos produced in a fission reactor and succeeded in doing it in 1954, thus ushering in the experimental study of neutrinos. They used inverse beta decay for the detection. The antineutrino is absorbed by a proton, giving a positron and a neutron, both of which are detected by a delayed coincidence.

A very important result on neutrinos was obtained in the reactor neutrino experiment from CHOOZ in France. The reactor was so powerful (8 GW thermal) that the neutrino detector could be placed even 1 km away. The detected flux agreed with the calculated flux to within about 2 percent, thus showing that there was no oscillation upto 1 km. Although this was a null result, this proved to be a crucial one, in the context of three-neutrino mixing[1]. For details on this and other reactor experiments, see the article by **C.V.K. Baba** in this volume.

The combined data from solar, atmospheric and reactor neutrinos can be analysed in a three-neutrino frame-work, as has been discussed in several articles in this volume. For convenience, we shall collate the results in the next section.

6 Neutrino Mixing and Oscillations

The neutrino flavour states $|\nu_\alpha\rangle$, $\alpha = e, \mu, \tau$, are linear superpositions of the neutrino mass eigenstates $|\nu_i\rangle$, $i = 1, 2, 3$, with masses m_i:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \ ,$$

where U is the 3×3 unitary mixing matrix,

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \ldots (1)$$

This mixing matrix involves three angles θ_{12}, θ_{13} and θ_{23} and a CP-violating phase δ. Here c_{ij} (s_{ij}) refers to $\cos\theta_{ij}$ ($\sin\theta_{ij}$). There are additional phases for Majorana neutrinos; only one combination occurs in oscillation phenomena so that they are indistinguishable from Dirac neutrinos.

The neutrino oscillation phenomena depend on six parameters, which are the three mixing angles, the CP violating phase, and two mass-squared differences, δm^2_{21} and δm^2_{32}, where

$$\delta m^2_{ij} = m^2_i - m^2_j \ . \quad \ldots (2)$$

Under the hierarchy assumption

$$|\delta m^2_{21}| \ll |\delta m^2_{32}| \ , \quad \ldots (3)$$

which is satisfied a posteriori, one can show that the solar neutrino problem depends only on δm^2_{21}, θ_{12} and θ_{13}, while the atmospheric neutrino problem depends only on δm^2_{32}, θ_{23} and θ_{13}. Thus the two problems are coupled by the 1-3 mixing angle θ_{13}.

The non-observation of oscillations in the CHOOZ reactor experiment turned out to be crucial in determining the oscillation parameters. Within the 3-neutrino frame-work, this result could be interpreted as an upper bound[1] on $\sin^2 2\theta_{13}$. The currently accepted bound on this parameter is $\sin^2 2\theta_{13} < 0.13$. This resulted in an approximate decoupling of the solar and atmospheric neutrino problems and simplified the three-neutrino analysis considerably. In fact, the solar and atmospheric neutrino problems reduce to simple 2-neutrino oscillations in the 1-2 and 2-3 sectors respectively, in the first approximation.

The delimitation of the parameter space allowed by the combined analysis of solar, atmospheric and reactor neutrinos is shown in Fig. 2 and Table I.*These results summarise the achievements in neutrino oscillation physics so far*. Fig. 2 is also reproduced on the cover of this volume and is from the papers by J.N. Bahcall, M.C. Gonzalez-Garcia, and C. Peña-Garay[2].

The solar an d KamLAND data have been combined in the analysis since they both constrain the

1-2 mixing parameters. The atmospheric data that determine the parameters in the 2-3 sector are from Super-K alone; the K2K accelerator data also determine these parameters but do not constrain the Super-K results further. The CHOOZ reactor result gives the constraint on the 1-3 mixing parameters.

Table I
The presently known values (or limits) on the neutrino oscillation parameters. Also indicated are the major experiments that determined these values.

Parameter	Allowed Values	Best Fit Value
Atmospheric (Super-K) + K2K		
$\vert\delta m^2_{32}\vert \sim \vert\delta m^2_{31}\vert$	(1–5) $\times 10^{-3}$ eV^2	2.6×10^{-3} eV^2
$\sin^2 2\theta_{23}$	0.8–1.0	1.0
Solar (Cl, Ga, Super-K, SNO) + KamLAND		
δm^2_{21}	(4–30) $\times 10^{-5}$ eV^2	6.9×10^{-5} eV^2
$\sin^2 2\theta_{12}$	0.64–0.99	0.82
Reactor (CHOOZ + Palo Verde)		
$\sin^2 2\theta_{13}$	≤ 0.13	–

It is seen that δm^2_{21} is nearly two orders of magnitude smaller than δm^2_{32}, so that $|\delta m^2_{32}| \sim |\delta m^2_{31}|$. While the sign of δm^2_{21} is known to be positive, that of δm^2_{32} is yet to be determined. Furthermore, nothing is yet known about the important CP violating parameter δ since most of the oscillation phenomena studied so far are insensitive to it.

It should be mentioned that one more reactor neutrino experiment, namely KamLAND, has also played a crucial role recently. More than one solution for the relevant parameters was possible if one restricted oneself to the solar neutrinos alone. KamLAND in combination with the SNO solar neutrino experiment ruled out all the other solutions except the one given in Table I.

It is important to note that the oscillation probabilities for neutrino propagation in vacuum and in matter are different. In matter (especially of varying density), the probabilities are drastically changed because of the famous Mikheyev-Smirnov-Wolfenstein (MSW) effect. In particular, solar neutrinos, on their way from the solar core to the outside, pass through matter with very high densities; hence, for the parameters given in Table I, the MSW effect plays an important role.

Since all the results of the solar, atmospheric and reactor neutrino experiments could be consistently explained within the frame-work of three neutrinos, it seems that all that is required is more precision neutrino experiments to pin down the fundamental neutrino parameters. But a spanner was thrown into the works by the LSND experiment discussed in the next Section.

7 Accelerator Neutrinos

A very important and puzzling result was obtained at Los Alamos by the LSND collaboration[3] which, if confirmed, has the potential of opening new and as yet uncertain physics beyond the Standard Model of particle physics. A beam of 800 MeV protons was used to produce pi and K mesons which decay providing a copious supply of neutrinos, mainly of the mu-type. By placing a detector at a distance of 30 meters from the source of neutrinos, they looked for the appearance of electron type neutrinos above the background. While the solar, atmospheric and reactor neutrino experimental results mainly involved suppression of the dominant neutrino flux, the LSND experiment was the first to observe the *appearance* of a flavour which was not there in the first place.

The results from solar, atmospheric and reactor neutrinos together already account for two distinct mass-squared differences and three mixing angles, in short, for three-flavour oscillations. Given this result, subsequently confirmed by the KamLAND reactor and K2K accelerator experiments, the distance of 30 meters in LSND is too short a distance for the muon neutrino to oscillate unless there exists at least one more flavour of neutrino. Because of the constraints coming from the LEP experiment on the number of active neutrino flavours (= 3), a fourth neutrino, if it exists at all, has to be sterile with no interactions with other particles in the Standard Model of particle physics.

So far, other experiments that yielded positive evidence for neutrino oscillation were disappearance experiments where deficits in the expected rates and fluxes were seen. The LSND is the only experiment that has observed oscillations in the appearance mode as well, although it is difficult to reconcile the LSND results with a 3-neutrino flavour oscillation framework. However, its importance (both for flavour oscillations in general and for the detailed phenomenology in particular) cannot be overstated. Hence several experiments have been launched/are being built in order to confirm or refute the LSND result. Data from other experiments, especially from KARMEN2[4], have

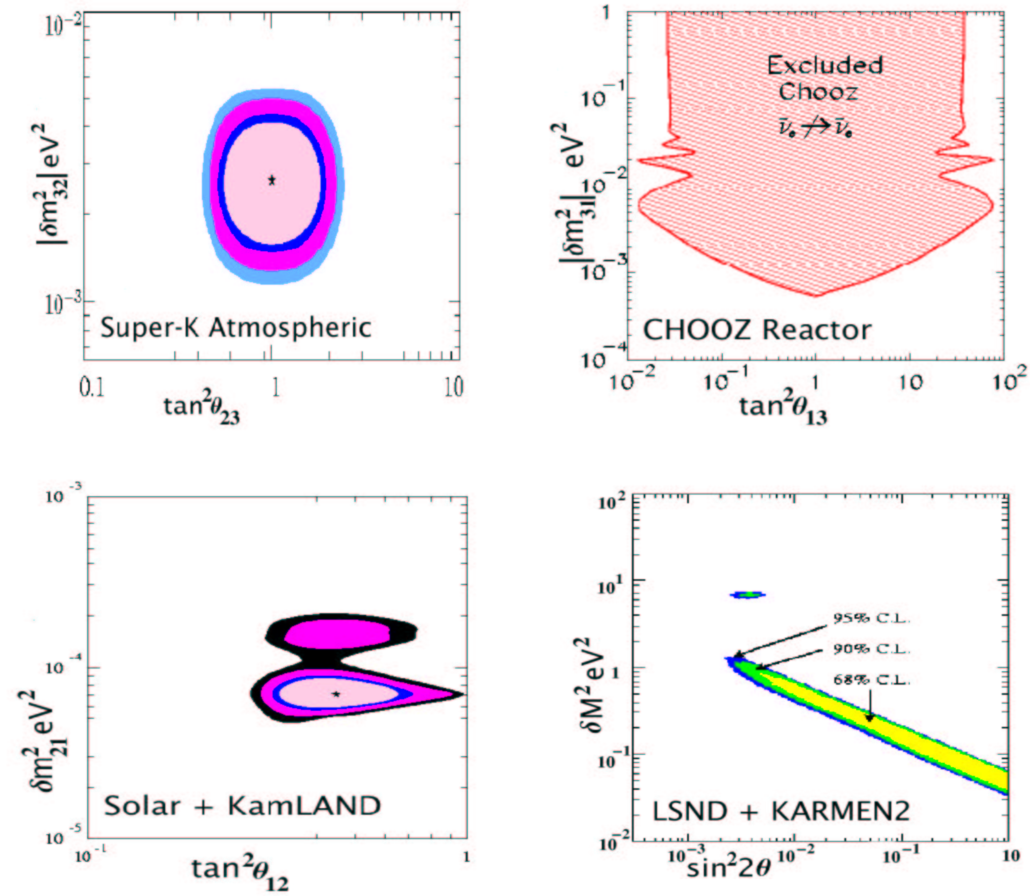

Fig. 2 The current neutrino parameter space allowed from solar, atmospheric, reactor and accelerator experiments[2]. For details, see the text.

already cut down a considerable part of the allowed parameter space of the LSND result. See Figure 2 for the allowed parameter space from a combined analysis of the LSND and KARMEN2 data; clearly, the allowed mass-squared difference is more than an order of magnitude larger than the corresponding one from solar or atmospheric neutrinos. The LSND result now awaits an independent confirmation or rebuttal from the highly sensitive MiniBooNE detector[5].

Accelerators are a copious source of neutrinos. Stopped protons produce pions and kaons that decay to produce muons and neutrinos. Information obtained on the neutrino oscillation parameters so far indicates that there is greater sensitivity, at the so-called long-baseline experiments, to the as-yet unknown parameters, which are the value of the 1-3 mixing angle, θ_{13}, the sign of the (32) mass-squared difference $(m_3^2 - m_2^2)$, observing matter effects on neutrino oscillation probabilities, and looking for CP violation in the lepton sector, apart from precision measurements of the magnitude of the mass-squared differences and the 2-3 mixing angle θ_{23}. An accelerator produces neutrinos, typically ν_μ (or its antiparticle) with a small ν_e contamination. A near detector normalises the flux of these neutrinos, while a detector placed far away (the far-end detector) makes the actual physics measurements, which may involve looking for electrons from CC interaction in the detector of ν_e produced by oscillation of ν_μ to ν_e in the beam. Preliminary data (confirming the oscillation hypothesis) already exists from the K2K experiment in Japan, where the source of the neutrino beam is in KEK, 250 km away from the far-end Super-Kamioka detector. The MINOS experiment in the U.S. is nearing completion, and others including ICARUS and OPERA are being planned in Europe. For more details on long baseline experiments, see the article by **S. Uma Sankar** in this volume.

Finally, there exist several groups around the world studying the possibility of building very long baseline experiments. Such experiments will be needed if θ_{13} is very small, and to observe Earth-matter effects and to disentangle them from CP violation effects. Such long baselines of several thousand kilometers necessitate the building of very high energy muon factories which will be the source of very energetic (with 10s of GeV energy) and focussed neutrinos beams that can be aimed at a detector virtually on the other side of the Earth. Details on such future possible neutrino factories are discussed in the article by **D. Indumathi** in this volume.

8 Geoneutrinos

Unfortunately, this important topic could not be covered in a separate article in this volume and so a brief account is included here.

Radiogenic heat from radioactive materials inside the Earth plays an important role in geodynamics. The observed heat outflow on the surface of the Earth is 40 TW and 40% of this (16 TW) is the estimated radiogenic contribution. Most of the radiogenic heat (90%) is believed to arise from the decays of U^{238} and Th^{232}.

Models of the Earth disperse 50% of U and Th in the mantle (2900 km thick) and concentrate the remaining 50% in a thin (35 km) crust under the continents, while the much thinner (6.5 km) oceanic crust is left poorer in U and Th. The continental crust is much thicker (about 75 km) under the Tibetan plateau.

But, all this is theory! An exciting possibility of *directly measuring* the amount of U and Th by their β-activities has opened up through the development of neutrino physics. This can be done by detecting the $\overline{\nu}_e$ emitted in β-decays of U and Th. An earlier proposal by Krauss, Glashow and Shramm[6] in 1984 was revived in the current context of neutrino detectors by Raghavan et al.[7] in 1998. See also the recent papers in ref.[7] on this subject.

In particular, Raghavan et al. pointed out that BOREXINO in Italy and KamLAND in Japan can be used for quantitatively measuring the amount of U and Th. Italy being on a continental crust, and Japan being on an oceanic crust, a confrontation with the above theoretical model prediction is possible. For the first time, the global U/Th distribution predicted by current geochemical models appears to be testable by experiment. In such an experiment, $\overline{\nu}_e$ from nuclear fission reactors on the surface of the Earth will provide a known background and hence can be used for calibration. The U and Th can actually be measured individually by a spectral signature, thus leading to the first global transuranic chemical analysis of the interior of the Earth.

Geoneutrinos have already been observed in the KamLAND experiment [9]. The low-energy component of the observed $\overline{\nu}_e$ spectrum in the KamLAND detector has a significant contribution from the radioactive decay of U and Th in the Earth. Mohanty[10] has analysed the spectral signature and determined the relative abundance of Th to U which has important information on the age of the Earth.

Raghavan[11] has drawn attention to the possibility of directly detecting the existence of a natural fission reactor at the centre of the Earth, that had been proposed as the energy source of the Earth's magnetic field. The experimental study of geoneutrinos may yield other surprises. A fantastic natural nuclear fission reactor that operated two billion years ago at the Oklo mine in Gabon, Africa, was accidentally discovered[12] some time ago. There may be other natural fission reactors somewhere that may still be running and future $\overline{\nu}_e$ detectors may reveal their existence!

One must also mention the possibility of neutrino exploration of the Earth[13]. Neutrino factories and very long baseline neutrino experiments can lead to tomography of the Earth.

9 Beta Decay and Neutrinoless Double Beta Decay

All the experiments, present and future, that we have discussed so far, will establish the presence of neutrino oscillations and constrain the neutrino mixing parameters. However, they will determine only mass-squared differences of the various mass eigenstates. A *direct* measurement of, or limit on, the neutrino masses has to come from other experiments. These are the beta decay experiments.

The end-point of the energy spectrum of the electrons in the beta decay of an appropriately chosen nucleus is sensitive to the neutrino mass. If we invoke our current understanding of flavour mixed eigenstates with nearly degenerate masses, then it is clear that bounds from beta decay are on a combination of masses, weighted by the appropriate entry in the neutrino mixing matrix. At present only upper limits are available: The most stringent upper limit for neutrino mass from beta decay is $\sim$ 2.2 eV. The corresponding upper limits from the muon and tau decay processes are 0.27 MeV and 18.2 MeV. Since oscillation data clearly show that the mass differences among the three neutrinos are very small, 2.2 eV can be regarded as the upper limit for all the three neutrino masses. Details on these direct mass measurements, especially the most sensitive one from tritium beta decay, are in the article by **V.M. Datar** in this volume.

Double beta decay is a novel phenomenon that distinguishes Dirac from Majorana neutrinos. Being electrically charge-neutral, among the particles of the Standard Model, neutrinos are the only fermions that can have Majorana behaviour, viz., be their own antiparticles. The possibility that neutrinos may be identical to antineutrinos has profound implications for neutrino physics and for models of neutrino masses and mixings. If neutrinos are Majorana, neutrino-less double beta decay ($0\beta\nu\nu$) can occur, when two electrons but no neutrinos are emitted. Such a non-zero $0\beta\nu\nu$ rate not only requires neutrinos to be Majorana but also requires that the relevant neutrino mass matrix element M_{ee} be non-vanishing; thus this process is a sensitive probe of the nature of the neutrino as well as this matrix element. Recently it has been claimed that such a non-zero rate has actually been measured at the Heidelberg-Moscow experiment. For more details, see the article by **H.V. Klapdor-Kleingrothaus** in this volume. This result has generated a lot of interesting controversy[14, 15]. Future planned detectors may refine the results and improve the error estimates.

10 Neutrinos in Astrophysics and Cosmology

Neutrinos are copiously emitted during stellar collapse–in fact, the first such observation of neutrinos from a supernova took place in 1987, opening a new window to understand stellar collapse as well as neutrino properties. Since this first observation, detailed studies of supernova neutrinos as a probe to study the oscillation mechanism have been done. Furthermore, neutrinos from supernovae are visible just beyond the energy range of solar neutrinos; hence they can be observed in detectors dedicated to solar neutrino experiments. A combination of observations from various such detectors will allow for a detailed analysis of the oscillation parameters. Conversely, if the oscillation parameters are already well-known, one can convert information on the stellar neutrino fluxes and spectra into information on supernova processes. All that is wanting is another supernova explosion! For more details, see the article by **Sandhya Choubey** and **Kamales Kar** in this volume.

The origin of high energy cosmic rays is unknown. Such cosmic rays, with energies exceeding 10^{20} eV, have been detected. Some of the proposals that attempt an understanding of the sources of high energy cosmic rays involve the possible role of neutrinos. Such neutrinos are massive and may exhibit new interactions; thus they may probe fundamental physics beyond the Standard Model. For details on various possible scenarios, see the article by **P. Bhattacharjee** in this volume.

If neutrinos are massive, they can have magnetic moments and thus be influenced by magnetic fields. Such a possible solution to the solar neutrino problem was proposed earlier but is now disfavoured by data. However, neutrinos can also be indirectly influenced by strong magnetic fields through their interaction with charged particles which are affected by the fields. Hence the rates for various neutrino processes may be modified in a background magnetic field.

This can have several astrophysical consequences. For instance, virtual photons may decay into a neutrino-antineutrino pair, thus providing a new way for energy emission in a star. Rates of neutrino production in a star may also be increased, so that the magnetic field enhances stellar energy loss. Neutrino oscillations may alter the calculations significantly, and in a direction-dependent way. Details of the modification of neutrino processes in the presence of magnetic fields are given in the article by **Kaushik Bhattacharya** and **Palash B. Pal** in this volume.

Relic neutrinos from the Big Bang are natural candidates for dark matter, which is an important component of the Universe. However, with the advent of new and amazingly accurate cosmic probes including the recent WMAP, cosmological data have increasingly constrained the role of neutrinos as dark matter. In addition, the data severely constrain their masses and types (number of neutrino species). In fact, these give the most stringent bound on the number of neutrino species, $2 < N < 4$, or $N < 3.2$, depending on the data used. Recall that the LEP constraint of $N = 2.994 \pm 0.0012$ is valid only for $\mathrm{SU}(2)_L$ doublet neutrinos and not for any other possible new type. For details on cosmological constraints on neutrino properties, see the article by **S. Sarkar** in this volume.

As already mentioned, existence of neutrinoless double beta decay, if established, will prove that the neutrino is a Majorana particle. This in turn would imply violation of lepton number, which would open a route to baryogenesis via leptogenesis in the early universe. (See the article **H.V. Klapdor-Kleingrothaus** and **U. Sarkar** in this volume.) Thus, while neutrinos are no longer considered to be candidates for dark matter, they may prove to be responsible for visible matter!

11 Models of Neutrino Masses and Mixing

Little is known about the origin of quark mixing and quark mass hierarchy. Less is known in the lepton sector since neutrinos, in addition, can be either Dirac or Majorana type particles. Hence different kinds of neutrino mass terms can be introduced into the Lagrangian of weak interactions, constrained, ultimately, by agreement with data. Various mechanisms for generating neutrino masses in gauge theories are discussed by **A.S. Joshipura** in this volume.

The experimental data on neutrino oscillations constrain the neutrino mass matrix to certain generic forms or patterns. Such a generic form of the neutrino mass matrix along with an underlying symmetry at some high scale is discussed by **E. Ma**.

The inclusion of Dirac masses for neutrinos extends the SM only marginally. However, the SM itself has many limitations, including a lack of understanding of the stabilisation of the Higgs boson mass. Supersymmetric extensions of the SM can cure this problem, but supersymmetry (SUSY) brings with it a host of new particles and their interactions. The structure of neutrino masses and interactions, in particular, is totally transformed in the presence of SUSY. Such supersymmetric models give predictions that are testable in accelerator based neutrino experiments. For more details, see the article by **B. Mukhopadhyaya** in this volume.

Many interesting consequences of neutrinoless double beta decay for neutrino masses and mixings are discussed by **H.V. Klapdor-Kleingrothaus** and **U. Sarkar** in this volume.

12 Non-Standard Neutrino Properties

Recall that all experiments so far have only seen a deficit (or an appearance, in the case of LSND) of some neutrino species. To confirm the oscillation hypothesis, it is important to be able to observe the oscillation pattern as a function of distance. In the meanwhile, it is relevant to ask whether non-standard, non-oscillation scenarios can fit the known data equally well. It appears that while non-oscillation scenarios such as spin-flavour precession and non-standard neutrino interactions including neutrino decay fit the solar neutrino data well, they are not consistent with recent reactor neutrino data from KamLAND. Hence, existing data can be used to place limits on neutrino instability as well as the possibility of CPT and Lorentz violation. A study of these exotic possibilities along with a detailed study of the implications of current data (solar, atmospheric, reactor and accelerator including LSND) on the conventional neutrino oscillations scenario is given in the comprehensive article by **S. Pakvasa** and **J.W.F. Valle**.

13 Outlook

Through this introduction we have given a bird's eye-view of the vast field of neutrino physics and have tried to put into perspective the major open issues in it. We have highlighted the results that indicate that neutrino flavours mix, have (distinct) masses, and therefore exhibit *neutrino flavour oscillations*, because this result is the first evidence for physics beyond the Standard Model of particle physics. We believe that a complete determination of neutrino masses and mixing parameters is simply a matter of time (even if it may take a decade or more); however, our understanding of the formal aspects of neutrino mass and mixing models is still rather incomplete. Finally, we have highlighted the role of neutrinos in astrophysics and cosmology. The articles in this volume provide the details to understand and appreciate various facets of this field.

References

1 Mohan Narayan, G Rajasekaran and S Uma Sankar *Phys Rev* D **58** (1998) 031301

2 J N Bahcall, M C Gonzalez-Garcia and C Peña-Garay *JHEP* 0302 (2003) 009 hep-ph/0212147; M C Gonzalez-Garcia preprint hep-ph/0211054 talk given at the 10th International Conference on Supersymmetry and Unification of Funda-

mental Interactions SUSY02 DESY Hamburg June 2002

3 C Athanassopoulos *et al* the LSND Collab *Phys Rev Lett* **81** (1998) 1774

4 B Armbruster *et al* the Karmen Collab *Phys Rev* D **65** (2002) 112001

5 A Bazarko the MiniBooNE Collab *Nucl Phys Proc Suppl* **91** (2000) 210

6 L M Krauss, S L Glashow and D N Schramm *Nature* **310**, (1984) 191

7 R S Raghavan *et al Phys Rev Lett* **80** (1998) 635

8 H Nunokawa *et al* hep-ph/0308175; F Mantovani *et al* hep-ph/0309013

9 K Eguchi *et al* the KamLAND Collab hep-ex/0212021 *Phys Rev Lett* **90** (2003) 021802

10 S Mohanty hep-ph/0302060

11 R S Raghavan hep-ex/0208038

12 M Maurette *Ann Rev Nucl Sci* **26** (1976) 319

13 A De Rujula, S Glashow, R Wilson and G Charpak *Phys Rep* **99** (1983) 341

14 C E Aalseth *et al Mod Phys Lett* A **17** (2002) 1475 hep-ex/0202018

15 H V Klapdor-Kleingrothaus hep-ph/0205228