Neutrinos and how to catch them

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Important developments have occurred recently in neutrino physics. These include the discovery of neutrino mass and the direct experimental proof of the thermonuclear hypothesis for the energy production mechanism in the Sun and other stars. These have led to world-wide plans for new neutrino laboratories. The India-based Neutrino Observatory (INO) is a project aimed at building a world-class underground neutrino laboratory. In this article we describe recent discoveries in neutrino physics as well as the INO project at an elementary level.

1 Introduction

Neutrinos are ghostly particles that can penetrate the whole Earth without getting stopped. They are everywhere in the Universe. In fact, trillions of neutrinos are passing through our body every second. All the stars including our Sun produce neutrinos copiously in their core. This is because the nuclear fusion processes that are the source of solar and stellar energy also generate neutrinos. Neutrinos are also produced by exploding stars (supernovae). Other sources of neutrinos include cosmic rays, nuclear reactors, particle accelerators and radioactive ore deep inside the Earth. In addition there are cosmic relic neutrinos from the birth of the Universe. The energy spectrum of the naturally produced neutrinos spans nearly thirty orders of magnitude, from 10^{-5} eV to 10^{25} eV.

Very important discoveries have been made recently in neutrino physics and neutrino astronomy. Neutrinos, which are the charge-neutral spin-1/2 particle emitted along with electrons (so-called beta-rays) in the radio-active decay of nuclei, were thought to be massless. The new discovery is that they are actually massive, although much lighter than any other particle including the electron. While there is now experimental proof, through the detection of solar neutrinos, that the Sun and other stars are powered by thermonuclear fusion reacions, the same experiments also clearly indicated that neutrinos exhibit the quantum-mechanical phenomenon called oscillation.

Impelled by these exciting discoveries, world-wide plans are being made now, for further studies of neutrinos and their properties: their masses, the nature of neutrino oscillation and the nature of the neutrino itself. India was a pioneer in neutrino experiments. In fact, cosmic-ray-produced neutrinos were first detected in the deep mines of Kolar Gold Fields (KGF) in 1965. Although the KGF experiments were closed down because of the closure of the mines, it is now planned to revive underground neutrino experiments in India. The India-based Neutrino Observatory (INO) is a project proposal for an underground laboratory that can house neutrino experiments.

We shall give an elementary review of the recent discoveries in neutrino physics and also describe the INO project. The article will attempt to paint an elementary picture of neutrinos and their interactions while highlighting the exciting discoveries that have been made and can yet be made in this field, and to enthuse students, scientists and engineers alike about the vast possibilities in neutrino physics in the world, and, in particular, at the future INO laboratory.

The plan of the article is as follows. After a brief history of neutrino physics, we take up solar neutrinos. Because of the historical importance of the solar neutrino problem and its solution, solar neutrinos are discussed in detail. This is followed by brief accounts of atmospheric, reactor and geo-neutrinos. Finally in section 9 we describe the INO project.

2 Brief History of Neutrino Physics

The chief landmarks in the history of neutrino physics are given below. We shall describe them in more detail in the rest of the article.

- 1930: Wolfgang Pauli proposes the existence of a neutral particle.
- 1932: Enrico Fermi gives it the name neutrino and constructs the theory of beta decay.
- 1956: Clyde Cowan and Frederick Reines detect the neutrino for the first time.
- 1965: The KGF experiment in India observes the neutrinos from atmosphere.
- 1967: Raymond Davis' experiment and the genesis of the solar neutrino problem.
- 1998: Discovery of neutrino mass by the Super-Kamioka experiment in Japan.
- 2002: Solution of the solar neutrino problem by the SNO detector in Canada.
- 2002: The KamLAND experiment in Japan confirms oscillations by a terrestrial experiment.
- 2005: Detection of geo-neutrinos by KamLAND.

Pauli proposed the existence of the neutrino in order to save the principle of conservation of energy in the beta decay of nuclei. He hypothesised that a neutrino is always produced along with the electron in nuclear beta decay. Fermi incorporated the notion of neutrinos into his theory of beta decay. Because of the success of Fermi's theory in explaining quantitatively all the experimental data on nuclear beta decays, there was hardly any doubt (at least in theorists' minds) that neutrinos existed; however, a direct detection of the neutrino came only in 1956. This achievement was due to Cowan and Reines who succeeded in detecting the antineutrinos produced from fission fragments in a nuclear reactor.

In 1965, neutrinos produced from cosmic-ray interactions with Earth's atmosphere were detected at KGF in India and later in many other experiments in the world. Solar neutrinos were detected by Davis et al. in 1967 in the U.S.A. and later by other detectors. The Kamioka detector in Japan and other detectors also observed neutrinos from the supernova explosion SN1987A. The Super-Kamioka detector discovered neutrino mass through the study of cosmic-ray-produced neutrinos in 1998, while the Sudbury Neutrino Observatory (SNO) in Canada solved the solar neutrino problem in 2002. The KamLAND detector in Japan confirmed the neutrino oscillation in a purely terrestrial experiment, using antineutrinos from nuclear reactors, in 2002 and the same detector detected geo-neutrinos in 2005.

3 Solar Neutrinos

In the 19th century, the source of the energy in the Sun and the stars remained a major puzzle in science, which led to many controversies. The answer to this question held the key to several related questions:

- What is the age of the Sun?

- This in turn is intimately related to the origin of life on Earth, since the ultimate source of energy for everything that happens on Earth is derived from the Sun.

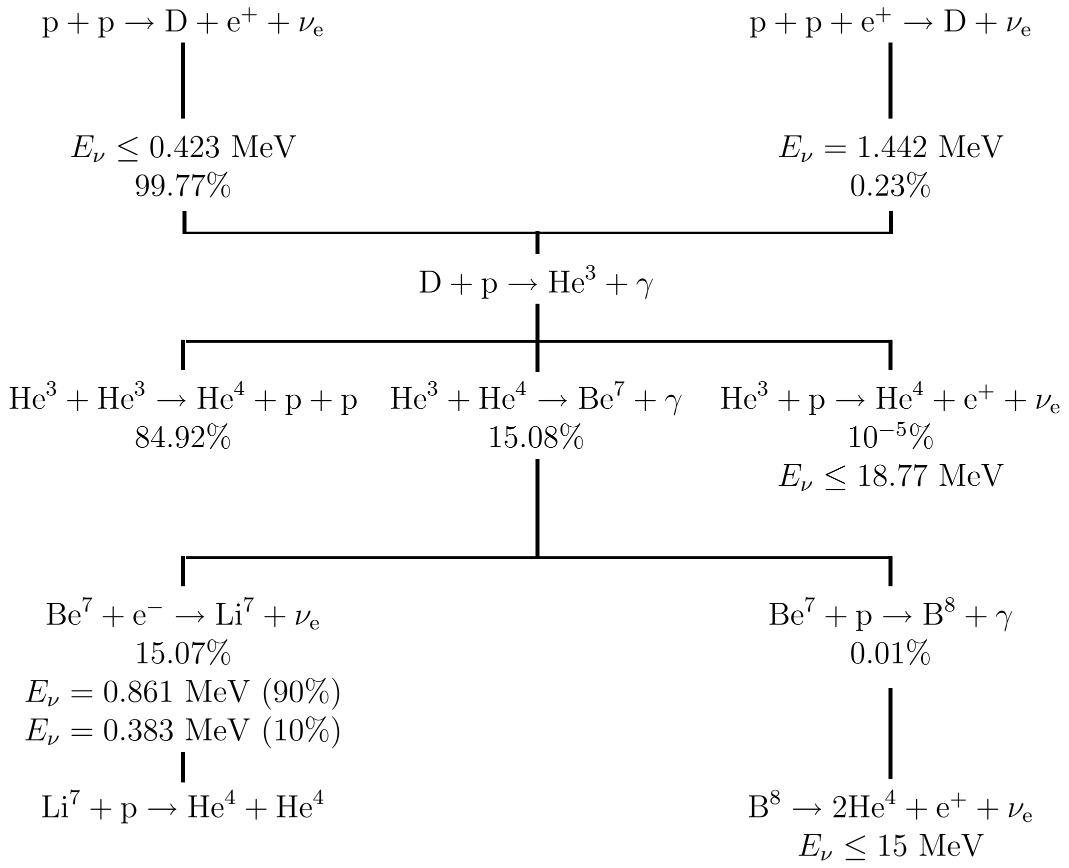
Charles Darwin had a crude estimate of the age of the Earth as about 300 million years old, based on the rate of erosion of the Wealds in the South of England. This seemed to Darwin long enough to produce the varied species on Earth through natural selection. This was contradicted by the physicists, most notably William Thomson, Lord Kelvin, at that time. Kelvin gave an estimate of 30 million years as the age of the Sun by calculating its gravitational energy divided by the rate at which the energy is radiated. Obviously the age of the Earth could not have been larger than the age of Sun. Certainly life on Earth could not have existed before the Sun! Finally the problem was solved only after the discovery of the atomic nucleus and the tremendous energy locked up inside the nucleus.

It was Arthur Eddington who, in 1920, suggested nuclear energy as the source of solar and stellar energy. It took many more years for the development of nuclear physics to advance to the stage when Hans Bethe, the Master Nuclear Physicist, analysed all the relevant facts and solved the problem completely in 1939. A year earlier, Carl von Weizsäcker had given a partial solution.

Bethe's paper is a masterpiece. It gave a complete picture of the thermonuclear reactions that power the Sun and the stars. However, a not-so-well-known fact is that Bethe omitted the neutrino that is emitted along with the electron, in the reactions enumerated by him. The neutrino, which became a part of Fermi's theory for beta decay, was already a well-known entity in nuclear physics. So it is rather inexplicable why Bethe ignored the neutrinos in his famous paper. The authority of Bethe's paper was so great that astronomers and astrophysicists who followed him in subsequent years failed to note the presence of neutrinos. Even many textbooks in Astronomy and Astrophysics written in the 1940s and 1950s did not mention neutrinos! This was unfortunate, since we must realize that, in spite of the great success of Bethe's theory, it is nevertheless only a theory. Observation of neutrinos from the Sun is the only direct experimental evidence for Eddington's thermonuclear hypothesis and Bethe's theory of energy production. Herein lies the importance of detecting solar neutrinos.

The basic process of thermonuclear fusion in the Sun and stars is four protons combining into an alpha particle and releasing two positrons, two neutrinos and 26.7 MeV of energy. However, the probability of four protons meeting at a point is negligibly small even at the large densities existing in the solar core. Hence the actual series of nuclear reactions occurring in the solar and stellar cores are given by the so-called pp chain (see Box 1) and the carbon-cycle (see Box 2). In the carbon cycle the four protons are successively absorbed in a series of nuclei, starting and ending with carbon. In the pp-chain two protons combine to form the deuteron and further protons are added. In the Sun, the dominant process is the pp-chain. In heavier stars, it is the carbon cycle.

Box 1: The pp chain.



$\mathrm{p + p \to D + e^+ + \nu_e}$

$E_\nu \leq 0.423$ MeV

99.77%

$\mathrm{p + p + e^+ \to D + \nu_e}$

$E_\nu = 1.442$ MeV

0.23%

$\mathrm{D + p \to He^3 + \gamma}$

$\mathrm{He^3 + He^3 \to He^4 + p + p}$

84.92%

$\mathrm{He^3 + He^4 \to Be^7 + \gamma}$

15.08%

$\mathrm{He^3 + p \to He^4 + e^+ + \nu_e}$

$10^{-5}\%$

$E_\nu \leq 18.77$ MeV

$\mathrm{Be^7 + e^- \to Li^7 + \nu_e}$

15.07%

$E_\nu = 0.861$ MeV (90%)

$E_\nu = 0.383$ MeV (10%)

$\mathrm{Li^7 + p \to He^4 + He^4}$

$\mathrm{Be^7 + p \to B^8 + \gamma}$

0.01%

$\mathrm{B^8 \to 2He^4 + e^+ + \nu_e}$

$E_\nu \leq 15$ MeV

In all branches of the pp chain, the net process is $\mathrm{4p \to He^4} + 2e^+ + 2\nu_\mathrm{e}$. Neutrino energies, both continuous and discrete, are indicated at the corresponding reaction or decay. The percentage numbers are the relative probabilities for the various branches, as calculated in the Standard Solar Model.

Box 2: The Carbon cycle.

$$\begin{aligned}
\mathrm{C^{12} + p} &\to \mathrm{N^{13} + \gamma} \\
&\quad \hookrightarrow \mathrm{C^{13} + e^+ + \nu_e} + 1.20 \text{ MeV} \\
\mathrm{C^{13} + p} &\to \mathrm{N^{14} + \gamma} \\
\mathrm{N^{14} + p} &\to \mathrm{O^{15} + \gamma} \\
&\quad \hookrightarrow \mathrm{N^{15} + e^+ + \nu_e} + 1.73 \text{ MeV} \\
\mathrm{N^{15} + p} &\to \mathrm{C^{12} + He^4}
\end{aligned}$$

The net process is $\mathrm{4p \to He^4} + 2e^+ + 2\nu_\mathrm{e}$. The neutrinos emitted in the beta decay of $\mathrm{N^{13}}$ have energies upto 1.2 MeV and those from $\mathrm{O^{15}}$ have energies upto 1.73 MeV.

Both in the carbon cycle and the pp-chain, the net process is the same, namely the fusion of four protons to form the alpha nucleus with the emission of two positrons and two neutrinos. The energy released is in the form of sunlight. So it is straightforward to calculate from the solar luminosity the total number of neutrinos emitted by the Sun; for "every" 26.7 MeV of energy, there must be 2 neutrinos. Such a calculation indicates that the solar neutrino flux at the Earth is 70 billion neutrinos per square cm per sec (this many pass through the size of your thumb-nail per second). So an enormous number of neutrinos are passing through our body!

Although the total number of neutrinos emitted by the Sun can be easily calculated from the solar luminosity, their energy dependence (spectrum) which is crucial for their experimental detection, requires a detailed model of the Sun, the so-called Standard Solar Model (SSM). The SSM is based on the thermonuclear hypothesis and Bethe's theory, but uses a lot more physics input. A knowledge of the neutrino energy spectrum is needed since the neutrino detectors are strongly energy sensitive. In fact all detectors have an energy threshold and hence miss out the very low energy neutrinos.

As can be seen from Fig. 1, the SSM predicts that the solar neutrino spectrum is roughly characterised by a dominant (99.75% of all neutrinos) low energy spectrum ranging upto 0.42 MeV and a very weak (0.01%) high energy part extending upto 14 MeV. The former arises from the pp reaction of two protons combining to form a deuteron, a positron and a neutrino. The latter comes from the beta decay of Boron-8 which is produced in a thermonuclear reaction initiated by a proton combining with Beryllium-7. Most of the neutrino detectors are able to detect only the tiny high-energy branch of the spectrum, the so-called Boron-8 neutrinos.

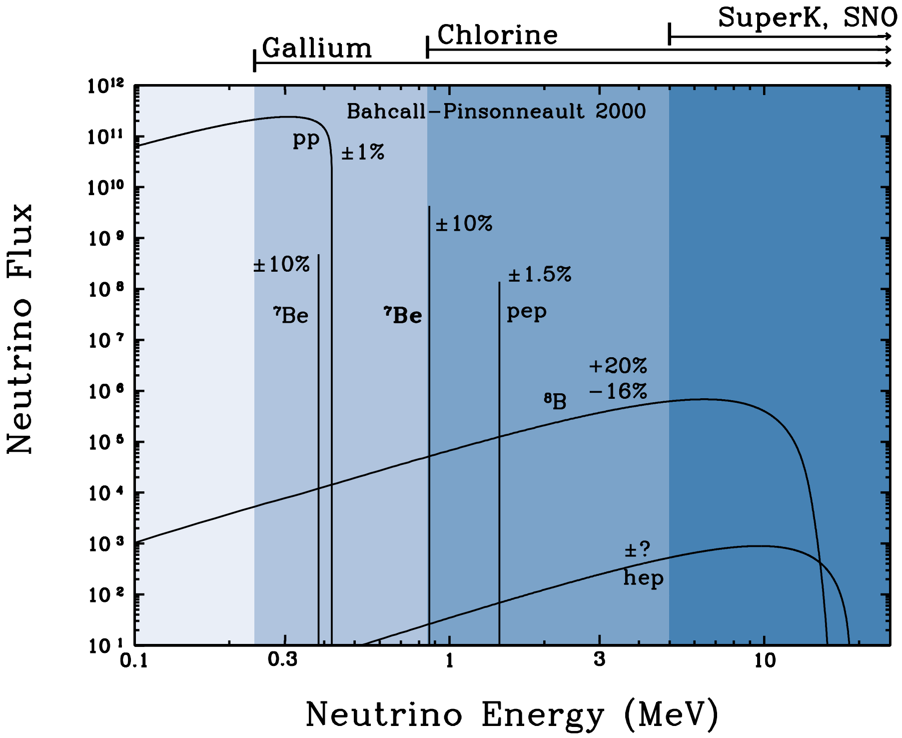


Figure 1: The neutrino flux in units of cm^{-2} sec^{-1} MeV^{-1} for the continuum neutrinos and cm^{-2} sec^{-1} for the neutrinos of discrete energy. The range of sensitivity of various detectors are also shown. The percentage numbers shown indicate the uncertainties in the calculated neutrino fluxes. Figure taken from the web-site of John Bahcall, http://www.sns.ias.edu/∼jnb/.

While the dominant low-energy neutrino flux is basically determined by the solar luminosity, the flux of the high-energy Boron-8 neutrino flux is very sensitive to the various physical processes in the Sun and hence is a test of the SSM. In fact, this latter flux is a very sensitive function of the temperature of the solar core, being proportional to the 18th power of this temperature and hence this neutrino flux provides a very good thermometer for the solar core. Since neutrinos are very weakly interacting, they emerge unscathed, carrying a great deal of information about the solar core, where they are produced. In contrast the sunlight that emerges from the solar surface does not carry any information about the solar interior.

There is a physical reason for this sharp dependence on temperature. It is related to the quantum-mechanical tunnelling formula, the famous discovery of George Gamow. The probability for tunnelling through the repulsive Coulomb barrier has a sharp exponential dependence on the kinetic energy of the colliding charged particles, which in turn depends on the temperature.

3.1 Solar neutrino experiments

Most neutrino detectors have to be placed deep underground so that the neutrino events are not swamped by the background (mostly from cosmic rays). Also, neutrino detectors have to be large in order to enhance observation rates.

The pioneering experiment on solar neutrinos started by Davis and collaborators in the 60's is based on the inverse beta decay process: Chlorine-37 absorbs the neutrino to yield Argon-37 and an electron. (See Box 3 for beta decay and inverse beta decay. See also the first figure in Box 4). A tank containing 615 tons of a fluid rich in chlorine called tetrachloroethylene was placed in the Homestake gold mine in South Dakota (U.S.A). Chlorine in the tank is converted into argon by the solar neutrinos. The fluid was periodically purged with Helium gas to remove the argon atoms which were then counted by means of their radioactivity. In a typical series of 62 runs during 1970-1983, the number of radioactive Argon-37 atoms detected per day was 0.44 ± 0.04. Of this, 0.08 ± 0.03 was attributed to cosmic ray and other background and so the number of argon atoms produced by solar neutrino capture was 0.36 ± 0.05 per day. These numbers give an idea of the fantastic achievement of Davis in devising methods of extracting so few argon atoms (about one in three days) and counting them. No wonder it has been likened to finding a particular grain of sand in the whole of the Sahara desert!

The detection threshold in Davis's experiment was 0.8 MeV and thus only the high-energy Boron-8 neutrinos were detected. The SSM could be used to get the number of neutrinos expected above this threshold and the detected number was less than the predicted number by a factor of about 3. Over the three decades of operation of Davis's experiment, this discrepancy remained and could not be satisfactorily accounted for by modifcations to the SSM and was thus known as the solar neutrino puzzle.

Davis's radiochemical experiment was a passive experiment. There was actually no proof that he detected any solar neutrinos. In particular if a critic claimed that all the radioactive atoms that he detected were produced by some background radiation, there was no way of conclusively refuting it. That became possible through the Kamioka experiment that went into operation in the 80's.

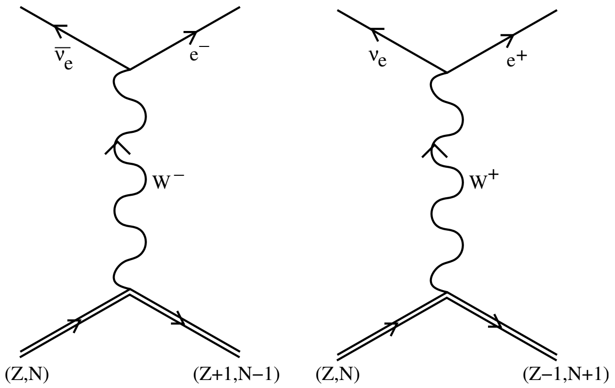
In contrast to Davis's chlorine tank, the Kamioka water Cerenkov detector is a real time detector. Solar neutrinos kick out electrons in the water molecule (elastic scattering) and the electrons are detected through the Cerenkov radiation they emit. Since the electrons are mostly kicked toward the forward direction, the detector is directional. A plot of the number of events versus the angle between the electron track and the instantaneous direction of the Sun gives an unmistakable peak at zero angle, proving that neutrinos from the Sun were being detected.

The original Kamioka detector had 2 kilotons of water and the Cerenkov light was collected by an array of 1000 photomultiplier tubes, each 20" in diameter. This was later superseded by the Super-Kamioka detector which had 50 kilotons of water faced by 11,000 photomutiplier tubes. Both Kamioka and Super-Kamioka gave convincing proof of the de-

Box 3: Beta decay and inverse beta decay.

$$\begin{array}{rcll}
(Z,N) & \rightarrow & (Z+1,N-1)+e^-+\overline{\nu}_e & (\beta^- \text{ decay}) \\
\mathrm{n} & \rightarrow & \mathrm{p}+e^-+\overline{\nu}_e & (\text{neutron } \beta^- \text{ decay}) \\
\nu_e+(Z,N) & \rightarrow & (Z+1,N-1)+e^- & (\text{Inverse } \beta^- \text{ decay})
\end{array}$$

$$\begin{array}{rcll}
(Z,N) & \rightarrow & (Z-1,N+1)+e^++\nu_e & (\beta^+ \text{ decay}) \\
\overline{\nu}_e+(Z,N) & \rightarrow & (Z-1,N+1)+e^+ & (\text{Inverse } \beta^+ \text{ decay}) \\
\overline{\nu}_e+\mathrm{p} & \rightarrow & \mathrm{n}+e^+ & (\text{Cowan-Reines reaction})
\end{array}$$



(Z,N) represents a nucleus with Z number of protons and N number of neutrons. In the figure, β^- and β^+ decays are shown diagrammatically. Here W^- and W^+ are charged intermediate weak bosons. If the direction of the arrows in the neutrino lines are reversed, and $\overline{\nu}_e$ and ν_e interchanged, they will represent the inverse β decay reactions.

tection of solar neutrinos. The energy threshold of these detectors was about 7 MeV and so only the high-energy part of the Boron-8 spectrum was detected. The ratio of the measured solar neutrino flux to the predicted flux was about 0.5. Hence, fewer solar neutrinos than predicted were detected, thus confirming the solar neutrino puzzle.

The next input came from the gallium experiments. The Boron-8 neutrino flux is very sensitive to the details of the SSM and so inadequacies in the SSM could be blamed for the detection of a lower flux. On the other hand the low energy pp neutrinos are not so sensitive to the details of the SSM. So the gallium detector based on the inverse beta decay of Gallium-71 was constructed. Although this was also a passive radiochemical detector, its threshold was 0.233 MeV and hence it was sensitive to a large part of the pp flux extending up to 0.42 MeV. Actually two gallium detectors, called SAGE and GALLEX, were mounted and both succeeded in detecting the pp neutrinos in addition to the B-8 neutrinos but again at a depleted level.

To sum up, there were three classes of neutrino detectors with different energy thresholds, all of which detected solar neutrinos, but at a depleted rate. The ratio R of the measured flux to the predicted flux was 0.33 ± 0.028 in the chlorine experiment, 0.56 ± 0.04 in the two gallium experiments (average) and 0.475 ± 0.015 in the SuperK experiment.

Actually it must be regarded as a great achievement for both theory and experiment that the observed flux was so close to the theoretical one, especially considering the tremendous amount of physics input that goes into the SSM. After all, R does not differ from unity by orders of magnitude! This is all the more significant since the large uncertainties in some of the low energy thermonuclear cross-sections do lead to a large uncertainty in the SSM prediction. But astrophysicists led by Bahcall were ambitious and claimed that the discrepancy is real and must be explained. Two points favour this view. As already stated, the gallium experiments sensitive to the pp flux which is comparatively free of the uncertainties of SSM, also showed a depletion in the flux. Second, SSM has been found to be very successful in accounting for many other observed features of the Sun, in particular the helioseismological data i.e., data on solar quakes.

Hence there must be some other reason why the ratio R of the observed and predicted events is less than unity and this must have something to do with the neutrino properties rather than the solar model. While many reasons have been propounded over the years, the currently most favoured one is the theory of neutrino oscillation.

3.2 Resolution of the solar neutrino puzzle

In addition to the well-known electron, two heavier types of electrons are known to exist. Reserving the name electron to the well-known particle of mass 0.51 MeV, the heavier ones are called muon and tau and their masses are 105 and 1777 MeV respectively. (For comparison, recall that the proton mass is 938 MeV). Correspondingly there are neutrinos of three types or flavours called ν_e, ν_μ and ν_τ respectively, that accompany the electron (e), muon (μ) and the tau (τ) in beta decay as well as inverse beta decay interactions. These particles, together called leptons, are listed as follows:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} .$$

What is produced in the thermonuclear reactions in the Sun is the electron neutrino, ν_e. If some of the ν_e oscillate to the mu- or the tau-neutrinos on the way to the Earth, the depletion in the number detected can be explained, since the chlorine and gallium detectors cannot detect the mu- or tau-neutrinos. Just as the electron-neutrino produces an electron in the inverse beta decay process, the mu- or tau-neutrino has to produce a muon or a tau respectively in the final state (See Box 4). But the energy of the solar neutrinos are limited to 20 MeV, and so the muon or tau with the high masses of 105 and 1777 MeV cannot be produced in the inverse beta decay and so the solar neutrinos that have been converted into the mu- or tau-neutrino through oscillation escape detection.

In contrast, elastic scattering of neutrinos on electrons, which is used as the detecting mechanism in the Kamioka and SuperK water Cerenkov detectors, can detect the converted ν_μ or ν_τ also, although it has a much reduced efficiency. Hence the depletion of the number of neutrinos observed in the water detector also is attributable to oscillation.

There is a story about a famous painting called “The Cow and Grass”. But nothing except a blank canvas was visible. When asked to show the grass, the painter said the cow had eaten the grass. When pressed to show at least the cow, he said it went away after eating the grass.

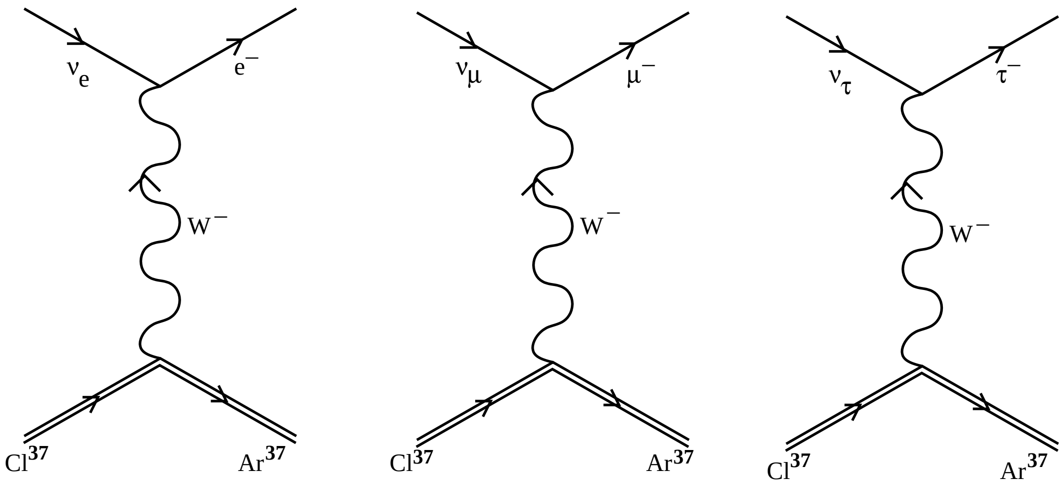
Our neutrino story so far is like that. We said thermonuclear reactions in the Sun must produce so many neutrinos. We did not see so many neutrinos, but then explained them away through oscillations.

In Science we have to do something better. If we say that neutrinos have oscillated into some other flavour, we have to see the neutrinos of those flavours too.

This is precisely what is done in a two-in-one experiment.

As shown in Box 5, there are two kinds of weak interaction processes. In beta decay a nucleus decays into another nucleus producing a neutrino along with an electron. In the related inverse beta decay, a neutral neutrino colliding with a nucleus leads to a charged lepton

Box 4: Neutrino-Chlorine interactions.



Reactions on Cl^{37} induced by the three flavours of neutrinos. At low energies of the order of a few MeVs, only the ν_e can induce the reaction.

(electron) and a different nucleus. These are both charged current (CC) weak interaction processes. There is a second type of weak interaction known as neutral current (NC) weak interaction in which the neutrino colliding with the nucleus excites or disintegrates it but remains as the neutrino in the final state, i.e., no charge change occurs.

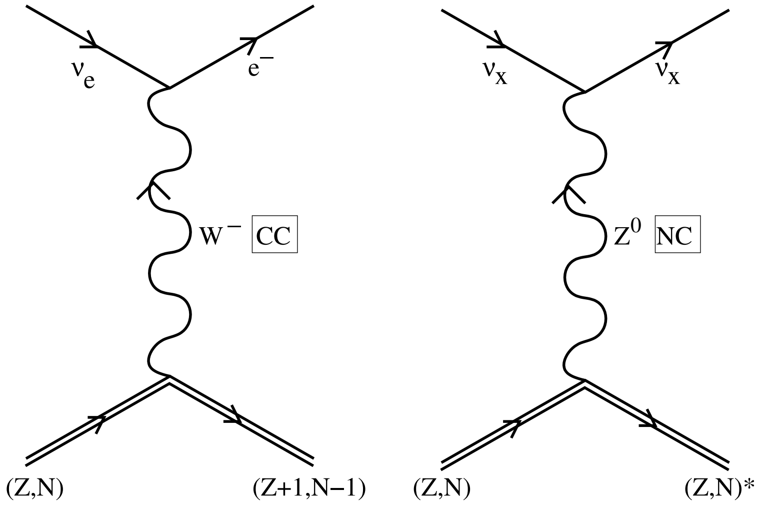
A low energy mu- or tau-neutrino cannot participate in a CC interaction with a nucleus as we already explained, but it can cause a NC interaction. So if we design an experiment in which both the CC and NC modes are detected, the CC mode will give involve only the electron-neutrinos, while the NC mode will count the total number of ν_e, ν_μ and ν_τ. This total number detected will be a test of the SSM independent of oscillations while the difference in the NC and CC events will give the number that have oscillated away.

A huge two-in-one (CC and NC) detector (BOREX) was proposed by Sandip Pakvasa and R. Raghavan but that has not materialised. The two-in-one detector based on deuteron in heavy water proposed by Herbert Chen has come up. This is the Sudbury Neutrino Observatory (SNO) that has finally solved the solar neutrino problem.

SNO uses 1000 tons of heavy water. Solar neutrinos interact with the deuteron through CC and NC modes. Deuteron or heavy hydrogen contains one proton and one neutron loosely bound in the nucleus. In the CC interaction with solar neutrinos, the neutron is converted into a proton so that the final state has two protons and an electron. In the NC interaction, the neutrino simply breaks up the deuteron while itself remaining unchanged. So the final state now consists of a single neutron and proton along with the neutrino. All interactions are detected by photomultiplier tubes covering the inside surface of the detector (See fig. 2). The threshold of detection was again high as in SuperK so that only the Boron-8 neutrinos were detected. The exciting results of SNO were published in April 2002.

The CC mode gave the flux as 1.76±0.11 million neutrinos/cm^2/s while the NC mode gave 5.09±0.65 in the same units. Thus we conclude that the flux of $\nu_e + \nu_\mu + \nu_\tau$ is 5.09±0.65 while that of the ν_e flavour alone is 1.76±0.11. The difference 3.33±0.66 is the flux of the $\nu_\mu + \nu_\tau$ flavours. Hence oscillation is confirmed. Roughly two third of the ν_e have oscillated to the other flavours. Furthermore, the NC results are consistent with the SSM predictions of 5.05±0.40. So in one sweep the SNO results confirmed both the Standard Solar Model (SSM) and the hypothesis of neutrino oscillation.

Box 5: CC and NC interactions.



The figure on the left shows a typical charged current (CC) interaction while that on the right shows a neutral current (NC) interaction. Here ν_X stands for ν_e, ν_μ or ν_τ, while W and Z are the charged and neutral weak bosons respectively.

What is the moral of the story? When we said in the beginning that the thermonuclear hypothesis for the Sun has to be proved, it was not a question of proof before a court of law. Science does not progress that way. In trying to prove the hypothesis experimentally through the detection of solar neutrinos, Davis and the other physicists have helped in making a discovery of fundamental importance, namely that the neutrinos oscillate and hence have mass. We will try to understand this better in the next section.

4 What is Neutrino Oscillation?

To understand neutrino oscillation, one must think of neutrino as a wave rather than than a particle (remember quantum mechanics). Neutrino oscillation is a simple consequence of its wave property. Let us consider the analogy with light wave. Consider a light wave travelling in the z-direction. Its polarisation could be in the x-direction, y-direction or any direction in the x-y plane. This is the case of the plane-polarised wave. However the wave could have circular polarisation too, either left or right. Circular polarisation can be composed as a linear superposition of the two plane polarisations in the x and y directions. Similarly plane polarisation can be regarded as a superposition of the left and right circular polarisations.

Now consider a plane polarised wave travelling through an optical medium. During propagation through the medium, it is important to resolve the plane polarised light into its circularly polarised components since it is the circularly polarised wave that has well-defined propagation characteristics such as the refractive index or velocity of propagation. In fact in an optical medium, waves with the left and right circular polarisations travel with different velocities. And so when light emerges from the medium, the left and right circular polarisations have a phase difference proportional to the distance travelled. If we recombine the circular components to form plane polarised light, we will find the plane of polarisation to have rotated from its initial orientation. Or, if we start with a polarisation in the x-direction,

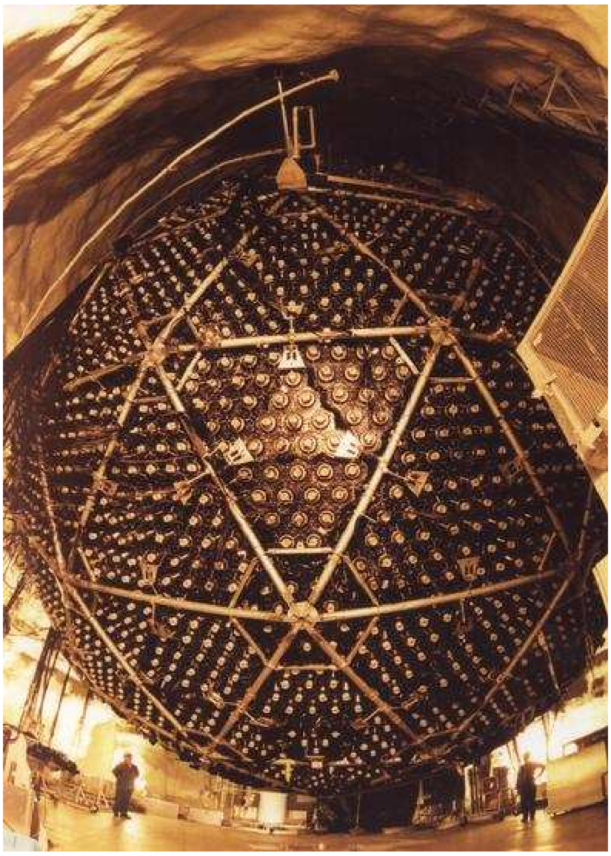


Figure 2: A photo of the SNO detector; photo courtesy of SNO.

a component in the y-direction would be generated at the end of propagation through the optical medium.

For the neutrino wave, the analogues of the two planes of polarisations of the light wave are the three flavours (ν_e, ν_μ or ν_τ) of the neutrino (see Table 1). When neutrinos are produced in thermonuclear reactions in the solar core, they are produced as the e-type. When the neutrino wave propagates, it has to be resolved into the analogues of circular polarisation which are energy eigenstates or mass eigenstates of the neutrino. These states have well-defined propagation characteristics with well-defined frequencies (remember frequency is the same as energy divided by Planck's constant). The e-type neutrino wave will propagate as a superposition of three mass eigenstates which pick up different phases as they travel. At the detector, we recombine these waves to form the flavour states. Because of the phase differences introduced during propagation, the recombined wave will have rotated "in flavour space". In general, it will have a ν_μ component and ν_τ component in addition to the ν_e component it started with. This is what is called neutrino oscillation or neutrino flavour conversion through oscillation. In contrast to the case of a light wave, it is important to realise that such oscillations occur even when the neutrinos are propagating in vacuum.

Light wave	Neutrino wave
Plane polarisation: x or y	Flavour state: ν_e, ν_μ, or ν_τ
circular polarisation: right or left	mass eigenstates: ν_1, ν_2, or ν_3

Table 1: The analogy between light wave and neutrino wave.

Flavour conversion is directly due to the phase difference arising from the frequency difference or energy difference which in turn is due to the mass difference. Mass difference cannot come without mass. Hence discovery of flavour conversion through neutrino oscillation amounts to the discovery of neutrino mass. This is the fundamental importance of neutrino oscillation, since so far neutrinos were thought to be massless particles like photons.

Since it is an oscillatory phenomenon, the probability of flavour conversion is given by oscillatory functions of the distance travelled by the neutrino wave, the characteristic "oscillation length" being proportional to the average energy of the neutrino and inversely proportional to the difference of squares of masses. Furthermore, the overall probability for conversion is controlled by the mixing coefficients that occur in the superposition of the mass eigenstates to form the flavour states and vice versa. These mixing coefficients form a 3×3 unitary matrix.

Neutrino oscillations during neutrino propagation in matter, for example, through the Earth, become much more complex and richer in physics, but we shall not go into details here. However it is important to mention two points. After L. Wolfenstein pointed out the important effect of matter on the propagating neutrino and S.P. Mikheyev and A. Yu. Smirnov drew attention to the dramatic effect on neutrino oscillation when the neutrino passes through matter of varying density, it was Bethe who gave an elegant explanation of the MSW (Mikheyev-Smirnov-Wolfenstein) effect, based on quantum mechanical level-crossing. In fact most people appreciated the beauty of MSW effect only after Bethe's paper appeared.

The second important point about the matter effect is the possibility of neutrino tomography. Neutrinos are the most penetrating radiation known to us. A typical neutrino can travel through a million Earth diameters without getting stopped. However because of the MSW effect the neutrino senses the density profile of the matter through which it travels and so the flavour composition of the final neutrino beam can be decoded to give information about the matter through which it has travelled. Hence tomography of the Earth's interior through neutrinos will be possible. Of course this requires our mastery of neutrino technology. But neutrino technology will be mastered and neutrino tomography will become a reality eventually!

5 Atmospheric Neutrinos

Solar neutrinos have energies in the MeV range. We now shift to more energetic neutrinos with 1000 times as much energy, that is, neutrinos in the GeV range. Cosmic rays, which are mostly protons, collide with the nitrogen and oxygen nuclei of the Earth's atmosphere and produce a large number of pions which ultimately decay into neutrinos, muons and electrons. These cosmic-ray-produced neutrinos are called atmospheric neutrinos. A pioneering experiment was done in India more than 40 years ago. This was the underground cosmic ray experiment in the Kolar Gold Field (KGF) mine which is one of the deepest mines in the world. When the experiment was done at deeper and deeper levels, the cosmic ray detector became silent at a certain depth. It was realized that at that depth and beyond, the other cosmic ray produced particles such as muons were completely shielded by the overlying rock (a few km thick) and hence at such depths one reaches the capability of detecting the cosmic-ray-produced neutrinos. In fact, even those neutrinos that are produced in the atmosphere on the far side of the Earth can be detected! The experimenters went ahead and did detect the neutrinos. That was in 1965.

Detailed studies of these atmospheric neutrinos were undertaken in many underground laboratories around the world in the succeeding decades. A well-known fact of weak interaction physics is that a pion mostly decays into a muon and a ν_μ. Subsequently the muon decays into an electron and two neutrinos, an e-type and a mu-type. So in the final debris of neutrinos detected deep underground, for every e neutrino there must be two muon-neutrinos. In other words, the ratio $R_{\mu/\mathrm{e}}$ of ν_μ to ν_e must be 2. The two types of neutrinos can be distinguished through their CC interactions in the detector when either an electron or a muon is respectively produced. Since the atmospheric neutrinos have energies in the GeV range, both types of neutrinos can induce CC reactions, in contrast to solar neutrinos.

The Kamioka water Cerenkov detector in Japan could distinguish between the electron and the muon and thus measure the ratio $R_{\mu/\mathrm{e}}$. It was found that the ratio was in fact 2 for the neutrinos detected in the downward direction, but it deviated considerably from 2 at other angles; in particular, the ratio was about unity for those neutrinos detected in the upward direction which have travelled around 13,000 km or the Earth's diameter. Although Kamioka detector and a few other detectors saw this discrepancy in 1990, it required the Super-Kamioka detector with its superior statistics to establish the effect in 1998.

The explanation of this anomaly is again neutrino oscillation. Since the anomaly was in the ratio of the fluxes of two types of neutrinos, unlike the solar neutrino problem before the advent of SNO, the inference of neutrino oscillation from the atmospheric neutrino anomaly was relatively free of the large uncertainties of the absolute flux. Hence in the discovery of neutrino mass through oscillation, SuperK and the atmospheric neutrino experiment won the race.

6 Reactor Neutrinos

A fission reactor is a copious source of neutrinos (actually electron-type antineutrinos from beta decay of fission fragments and neutrons). The very first experimental detection of neutrino was in fact made with reactor neutrinos by Cowan and Reines. They used inverse beta decay for the detection. The antineutrino is absorbed by a proton, giving a positron and a neutron (see Box 3), both of which are detected by delayed coincidence since the neutron decays slowly. The photons from positron annihilation and the decay products of the neutron are obseverd.

A very important result on neutrinos was obtained in 1998 in a reactor neutrino experiment at Chooz in France. The reactor was so powerful that the neutrino detector could be placed even 1 km away. The detected flux agreed with the calculated flux within about 2 percent, thus showing that there was no oscillation up to 1 km. Although this was a null result, this played a crucial role in the global analysis of neutrino oscillations.

In 2002, antineutrinos from a dozen power reactors in Japan were detected in a scintillation detector called KamLAND. Although the reactors were at various locations, their distances from the detector were around 180 km and at such a distance the antineutrinos must oscillate and this has been confirmed beautifully by this experiment.

7 How Large are the Neutrino Masses?

As we have mentioned, neutrino oscillation implies that neutrinos have non-zero (and different) masses. Three masses yield two mass-square differences. A combined analysis of the solar, atmospheric and reactor neutrino data has led to a rough determination of these two differences of neutrino mass-squares. The mass-square differences are found to be very tiny: about 2×10^{-3} and 8×10^{-5} eV^2. Also, many entries in the 3×3 mixing matrix have been determined, although there are still uncertainties to be resolved.

We do not yet know the values of the masses themselves, since only differences in neutrino mass-squares can be determined from the oscillation phenomena. However nuclear beta decay experiments can give the absolute masses, although so far they have led only to an upper limit to the neutrino mass and that limit is 2.2 eV. Hence we can say all the three neutrinos have very tiny masses, all below 2.2 eV, with even tinier mass-differences among them. Many experiments are being designed in order to determine the masses more precisely.

Finally we must mention that even the fundamental nature of the neutrino is still not known, namely whether neutrino is its own antiparticle or not. This question can be answered only by the "neutrinoless double beta decay experiment". So far, such experiments have not yielded definitive results and hence more experiments are being planned. This is an important area of future research.

8 Geoneutrinos

A new window on Geophysics was opened when KamLAND announced in July 2005 the first detection of geoneutrinos, that is antineutrinos from the radioactive uranium and thorium deposits buried in the Earth. It is believed that about 40 percent of the heat outflow from inside the Earth is due to the radioactive deposits. This is 16 terrawatts of power, with the corresponding flux of antineutrinos being 6 million per sq cm per sec. An exciting possibility of directly determining the amount of uranium and thorium deposits and their relative distribution in the mantle and crust of the Earth, through measuring the geoneutrino flux, has opened up. The experimental study of geoneutrinos may yield other surprises such as, for instance, the discovery of the existence of natural fission reactors at the centre of the Earth, as has been speculated.

9 India-based Neutrino Observatory–INO

Neutrino physics has made a spectacular beginning. There are still many unanswered questions. In order to make further progress there are many plans to start new neutrino experiments all over the world. We shall now give a brief account of the proposed INO Project.

INO is envisaged as a major collaborative project involving many institutions in India and abroad. More than 100 scientists and engineers from about 15 institutions have already joined the National Neutrino Collaboration but more are welcome to join. Although INO is primarily an Indian venture, international collaboration also will be an essential component.

The project involves building a huge neutrino detector in a laboratory under a mountain. After an initial period of study of various sites, one in the Nilgiri mountain in South India has been chosen. A huge cavern of size 100 m × 25 m × 30 m (ht) will be dug underneath the mountain at a depth of about 1.3 km below the peak and the detector will be placed inside the cavern. The cavern will be reached by a horizontal tunnel of 2 km length into which scientists and engineers can drive in and out easily, unlike in a mine. (See Fig. 3). Such a thick rock cover (more than 1 km all-around) is required for stopping the cosmic-ray particles other than neutrinos such as muons which will otherwise swamp the detector.

The detector itself will consist of 140 layers of 6 cm thick iron plates interleaved with 2.5 cm air gaps containing active detector elements (See Fig. 4). The dimensions will be 48 m × 16 m × 12 m (ht) and the weight about 50 ktons. The detector elements will be glass RPCs (Resistive Plate Chambers) which are gas-filled chambers with a high voltage across the plates. Atmospheric neutrinos will interact with the iron nuclei in the thick iron plates and produce electrons and muons via charged current interaction. These charged particles,

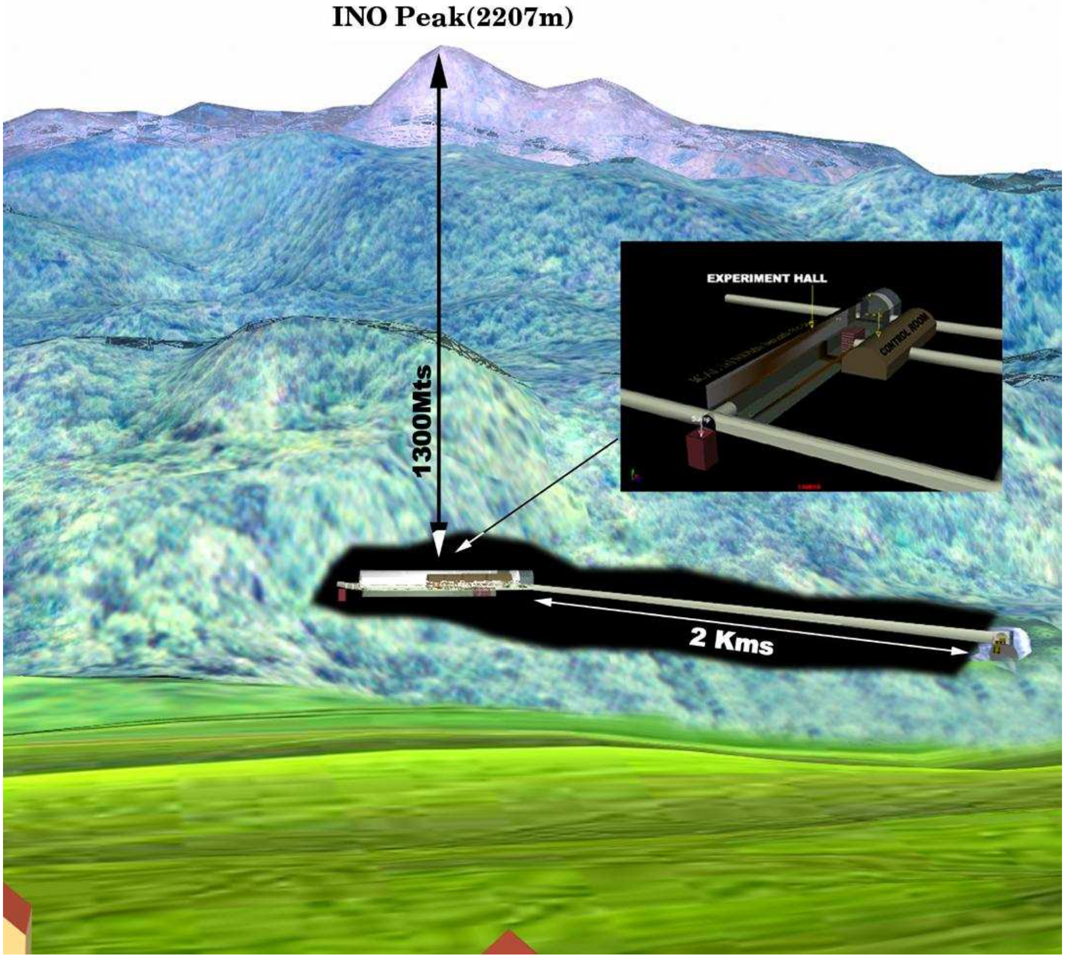


Figure 3: Schematic view of the the tunnel and cavern under the Nilgiri mountains.

on passing through the RPCs, will initiate a discharge that will be detected as a fast-rising electrical pulse. The positions where the pulses are triggered will indicate the track of the charged particle. The tracks can be calibrated to recover the energy and direction of the charged particles. Hence it is called an iron calorimeter (ICAL) detector. That is the simple principle behind this neutrino detector.

An important feature of the detector will be a high magnetic field of 1.2 Tesla generated by current-carrying coils surrounding the detector. This will lead to the separate identification of muons of positive and negative charges through their oppositely curved tracks in the magnetic field. Since neutrinos and antineutrinos produce oppositely charged muons in their charged-current interaction with nuclei, this detector has the capability of making a measurement of the fluxes of atmospheric neutrinos and antineutrinos separately. So far this has not been done by any other detector in the world. This is specially important since neutrinos and antineutrinos have different interactions with the Earth matter through which they travel.

In phase I of its operation, the INO detector will be used for studying atmospheric neutrinos and determining the relevant fundamental neutrino parameters (mass-square differences and mixing matrix) more precisely than what has been possible so far. An important measurement that ICAL can make is to study the oscillation pattern, through one complete period from maximum to the next maximum and so establish that neutrino oscillations ex-

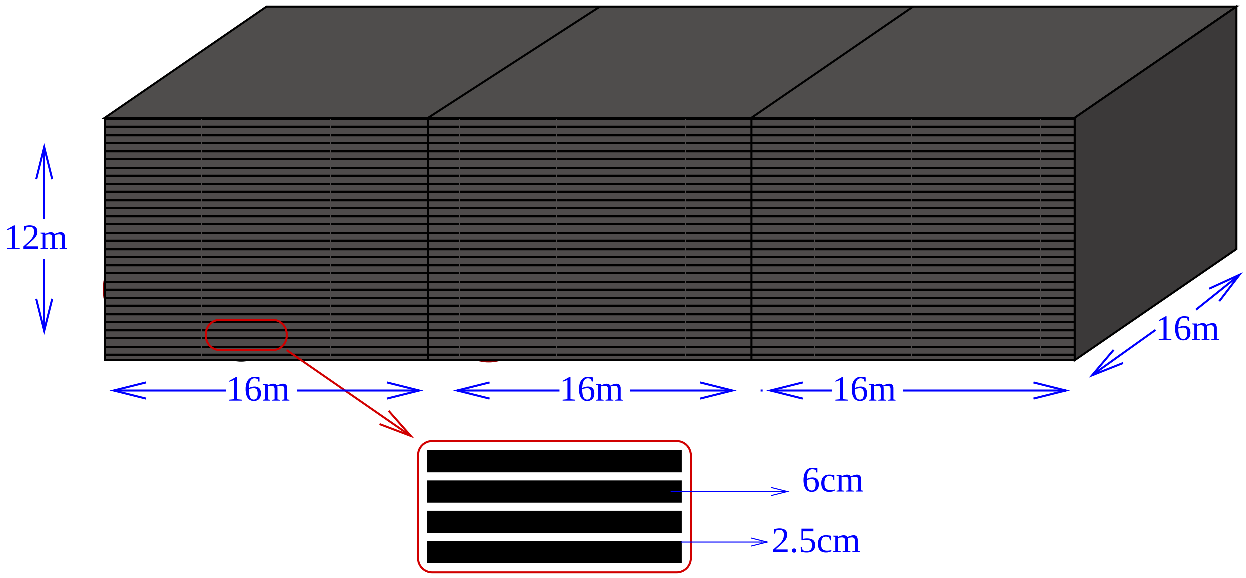


Figure 4: The proposed Iron Calorimeter (ICAL) detector at INO.

ist, not just from observed depletions, as has been done so far, but through observation of regeneration of the particular flavour (muon-type) as well.

Although we now know the three neutrinos to have different masses, we still do not know the order of the mass levels (See Fig. 5). Because of its unique ability to separate neutrino and antineutrino events as pointed out above, the magnetised iron detector has the capability of discovering the order of the three neutrino masses. Surely such a discovery (if it can be achieved) will be an important milestone in Neutrino Physics.

Phase II of the INO detector involves very long-term goals. Several groups around the world are discussing the possibility of so-called long-base-line experiments in which neutrinos produced in accelerators either in Japan, Europe or USA can be detected in detectors placed thousands of kilometres away. INO can be the location for such a far-end detector. If these plans materialise, then we will have base-line-lengths of 6,600 km, 7,000 km or 11,000 km respectively for Japan, Europe or USA to INO. Some of the important neutrino parameters can be determined only through oscillations over such long baselines. Furthermore the neutrino beam will pass through a considerable part of the Earth in these experiments and hence will become a tool for the tomography of the Earth.

INO may ultimately house more than one type of detector and many neutrino experiments may be conducted there. This is especially because of the vast range of energy over which interesting neutrino physics questions are being asked (from MeV neutrinos from the Sun and supernovae to GeV neutrinos from the atmosphere and accelerators to TeV neutrinos from ultra high energy cosmic rays). Plans are already being made for a neutrinoless double beta decay experiment in the INO cavern.

It is clear that INO will have a strong impact on experimental physics in the country over the next 25 years. What is needed are young scientists and engineers who will enjoy the challenge of setting up an entirely new facility for doing world class research. Now is the right time to join INO.

More information on INO is available at the INO web-site: http://www.imsc.res.in/∼ino.

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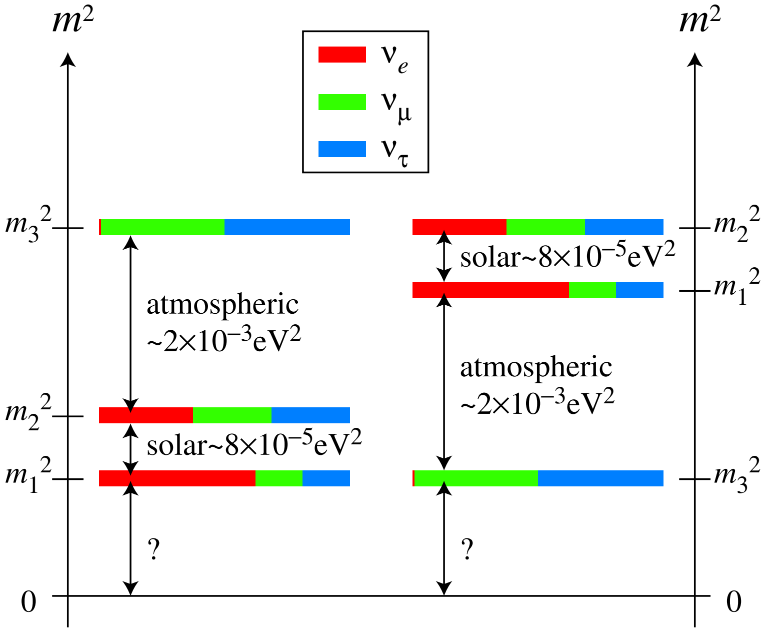

Figure 5: Schematic drawing of the two possible neutrino mass orderings currently permitted by data. The colour coding (degree of greyness) indicates the extent of mixing of ν_e, ν_μ and ν_τ flavours in each mass eigenstate. Taken from the APS multi-divisional neutrino study, 2004.

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