Hans Bethe, the Sun and the Neutrinos

G Rajasekaran

We give an elementary review of recent discoveries in neutrino physics, culminating in the solution of the solar neutrino problem and the discovery of neutrino mass. Atmospheric neutrinos, reactor neutrinos and other important developments are also briefly described.

G Rajasekaran is a theoretical physicist at the Institute of Mathematical Sciences, Chennai. His field of research is quantum field theory and high energy physics. Currently he is working in the area of neutrino physics.

1. Introduction

This is an elementary account of the recent discoveries in Neutrino Physics. Because of its historical importance and its role in the story of Hans Bethe, the genesis of the solar neutrino problem and its solution in terms of neutrino oscillation are described in greater detail. In particular, we trace the story of the 80-year-old thermonuclear hypothesis which states that the Sun and the stars are powered by thermonuclear fusion reactions. We describe how the Sudbury Neutrino Observatory in Canada was finally able to give a direct experimental proof of this hypothesis in 2002 and how, in the process, a fundamental discovery, i.e. the discovery of neutrino mass was made.

Atmospheric neutrinos and reactor neutrinos are important for a complete analysis of neutrino oscillations. These and many other equally important issues are briefly discussed at the end.

2. 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. Finally, after the discovery of the tremendous amount of energy locked up in the nucleus, Eddington in 1920 suggested nuclear energy as

Keywords
The Sun, thermonuclear fusion, neutrino oscillation, neutrino mass, INO.

How does the Sun shine? Thermonuclear fusion is the answer. But, observation of neutrinos from the Sun is the only direct experimental evidence for this hypothesis. That is the importance of detecting neutrinos.

the source of solar and stellar energy. It took many more years for the development of nuclear physics to advance to the stage when Bethe, the Master Nuclear Physicist, analysed all the relevant facts and solved the problem completely in 1939. A year earlier, Weiszäcker had given a partial solution.

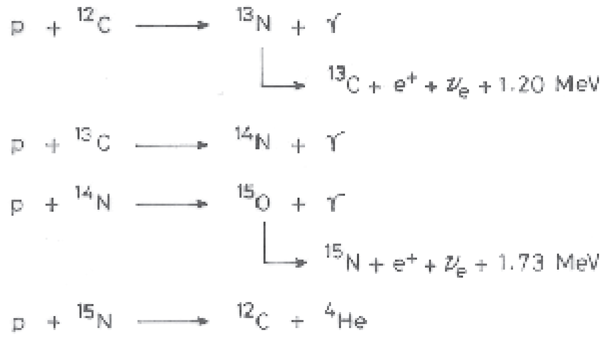
Bethe's paper is a masterpiece. It gave a complete picture of the thermonuclear reactions that power the Sun and the stars. However, a not-so-well-known fact is that Bethe leaves out the neutrino that is emitted along with the electron, in the reactions enumerated by him. Neutrino, born in Pauli's mind in 1932, named and made the basis of weak interaction by Fermi in 1934, 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 the astronomers and astrophysicists who followed him in the subsequent years failed to note the presence of neutrinos. Even many textbooks on astronomy and astrophysics written in the 40's and 50's do 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. That is the importance of detecting solar neutrinos.

Neutrino is the only particle that has only weak interactions and hence the extreme difficulty of its detection.

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. So it is trivial to calculate from the solar luminosity the total number of neutrinos emitted by the Sun; for 'every' 26.7 MeV of energy received by us, we must get 2 neutrinos. Thus one gets the solar neutrino flux at the Earth as 70 billion per square cm per sec. So an enormous number of neutrinos are passing through our body!

Box 1. Carbon Cycle

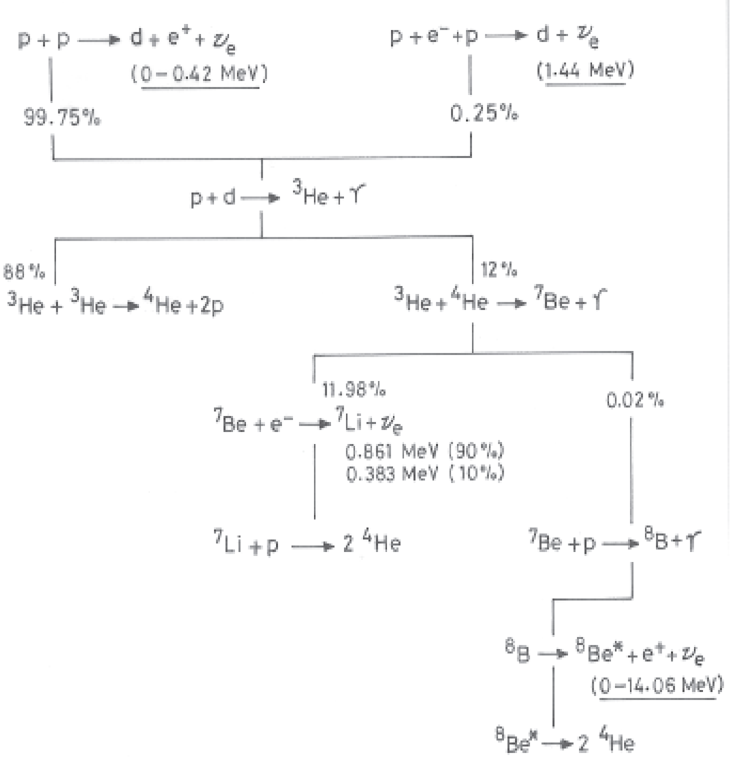
The net process is 4p→ ^{4}He + 2e$^+$ + 2ν_e. The neutrinos emitted in the beta decay of ^{13}N have energies of 0 to 1.20 MeV while those from ^{15}O range from 0 to 1.73 MeV.



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 occuring in the solar and stellar cores are given by the so-called carbon cycle (*Box* 1) and the p–p chain (*Box* 2). In the carbon cycle the four protons are successively absorbed in a series of nuclei, starting and

Box 2. p–p Chain

In all the branches of the p–p chain, the net process is 4p→^{4}He + 2e$^+$ + 2ν_e. Neutrino energies (both continuous as well as 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 (SSM).



ending with carbon. In the p–p chain two protons combine to form the deuteron and further protons are added. We shall not go into details here except noting that both in the carbon cycle and the p–p chain, the net process is the same as what was mentioned above, namely the fusion of four protons to form an alpha particle with the emission of two positrons and two neutrinos.

The net process is the fusion of four protons to form an alpha particle with the emission of two positrons and two neutrinos.

In the Sun, the dominant process is the p–p chain. Although the total number of neutrinos emitted by the Sun could be trivially calculated from the solar luminosity, their energy spectrum which is crucial for their experimental detection, requires a detailed model of the Sun, the so-called Standard Solar Model (SSM). 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. Infact all detectors have an energy threshold and hence miss out the very low energy neutrinos.

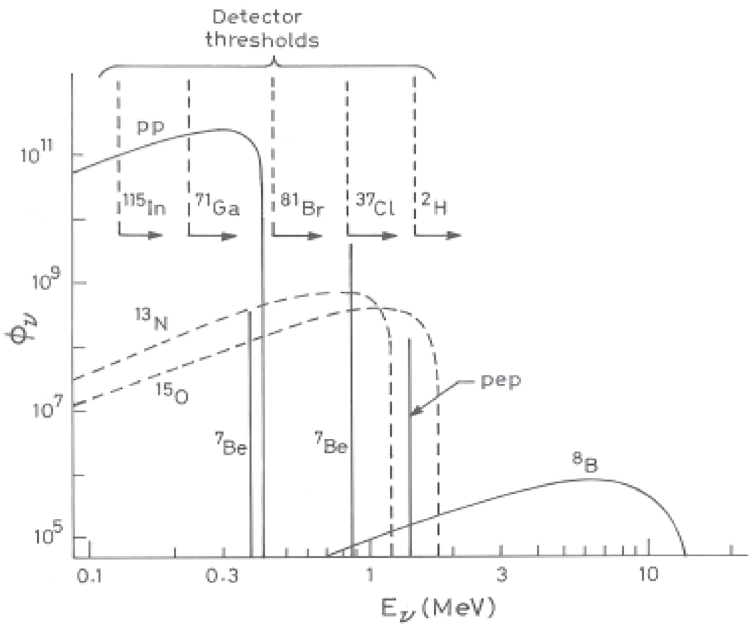
Leaving out the details, the solar neutrino spectrum is roughly characterized by a dominant (0.9975 of all neutrinos) low energy spectrum ranging from 0 to 0.42 MeV and a very weak (0.0001 of all the neutrinos) high energy part extending from 0 to 14 MeV (*Box* 3). The former arises from the p–p reaction 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 detect only the tiny high-energy branch of the spectrum, the so-called Boron-8 neutrinos.

The high energy flux of neutrinos from the Sun is proportional to the 18th power of the temperature in the solar core and hence is a very sensitive thermometer for the solar core.

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 SSM. Infact, this latter flux is a very sensi-

Box 3. Energy Spectrum of the Solar Neutrinos

The y axis represents the flux of the neutrinos 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 thresholds of various detectors are also shown.



tive 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. In contrast to the photons which hardly emerge from the core, the neutrinos escape unscathed and hence give us direct knowledge about the core.

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

The pioneering experiment on solar neutrinos started by Davis and collaborators in the 60's is based on the

Box 4. Beta Decay and Inverse Beta Decay

(Z,N) represents a nucleus with Z number of protons and N number of neutrons. At the bottom, β^- and β^+ decays are shown digrammatically. W^- and W^+ are charged intermediate weak bosons. If the direction of the arrows in the neutrino lines are reversed and $\bar{\nu}_e$ and ν_e changed to ν_e and $\bar{\nu}_e$ respectively, they will represent the inverse β decay reactions.

$(Z,N) \longrightarrow (Z+1,N-1) + e^- + \bar{\nu}_e$ (β^- decay)

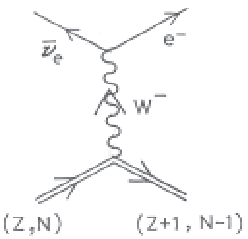
$n \longrightarrow p + e^- + \bar{\nu}_e$ (β^- decay of n)

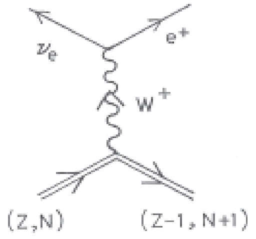
$\nu_e + (Z,N) \longrightarrow (Z+1,N-1) + e^-$ (Inverse β^- decay reaction)

$(Z,N) \longrightarrow (Z-1,N+1) + e^+ + \nu_e$ (β^+ decay)

$\bar{\nu}_e + (Z,N) \longrightarrow (Z-1,N+1) + e^+$ (Inverse β^+ decay reaction)

$\bar{\nu}_e + p \longrightarrow n + e^+$ (Cowan-Reines reaction)





inverse beta decay process: Chlorine-37 absorbs the neutrino to yield Argon-37 and an electron. (See *Box* 4 for beta decay and inverse beta decay.) A tank containing 615 tons of a fluid rich in chlorine called tetrachloroethylene was placed in the Homestake gold mine in South Dakota (USA). 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 level of achievement of Davis in devising methods of extracting the argon atoms 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. 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 has remained and has been known as the solar neutrino puzzle.

Out of the millions of high-energy neutrinos arriving per sec at Davis's huge tank of the detecting fluid, only about one neutrino per three days interacted. That is the meaning of 'weak interaction'.

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[1] that went into operation in the 1980's.

In contrast to Davis's chlorine tank, the Kamioka water Cerenkov detector is a real time detector. Solar neutrino kicks out an electron in the water molecule (elastic scattering) and the electron is detected through the Cerenkov radiation it emits. Since the electron is mostly kicked toward the forward direction, the detector is directional. A plot of the number of events against the angle between the electron track and Sun's direction 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 of 20" diameter and this was later superceded by the SuperKamioka detector which had 50 kilotons of water faced by 11,000 photomutiplier tubes. Both Kamioka and SuperK gave convincing proof of the detection 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 being detected. The ratio of the measured solar neutrino flux to the predicted flux was about 0.5, thus confirming the solar neutrino puzzle.

Over the 3 decades of operation of Davis's experiment, the discrepancy between the predicted and the detected numbers of solar neutrinos remained and was known as the solar neutrino puzzle.

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[1] See S N Ganguli, Neutrinos and our Sun, *Resonance*, Vol.9, Nos.2,3. 2004.

All the three classes of neutrino detectors with different energy thresholds detected the solar neutrinos, but at a depleted rate.

The next input came from the gallium experiments. The Boron-8 neutrino flux is very sensitive to the details of the SSM and so SSM could be blamed for the detection of a lower flux. On the other hand the low energy p–p neutrinos are not so sensitive to 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 p–p flux extending upto 0.42 MeV. Actually two gallium detectors were mounted, called SAGE and GALLEX and both succeeded in detecting the p–p neutrinos in addition to the B-8 neutrinos but again at a depleted level by a factor of about 0.5.

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.

John Bahcall who played a major role in the genesis of the solar neutrino problem and hammered at SSM for more than 30 years until it reached a precision suitable for its eventual confrontation with solar neutrino experiments died on 17 August 2005.

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 late John Bahcall were ambitious and claimed that the discrepancy was real and must be explained. Two points favour this view. As already stated, the gallium experiments sensitive to the p–p 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

Box 5.

Electron (e), muon (μ), tauon (τ)) and their associated neutrinos.

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \qquad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \qquad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$$

Sun, in particular the helioseismological data, i.e data on solar quakes.

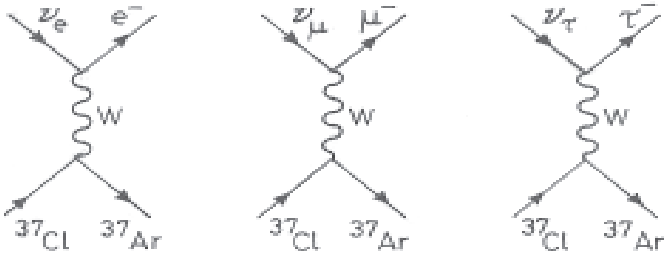
Hence something else is the reason for R being less than unity and that is neutrino oscillation.

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 0.5 MeV, the heavier ones are called muon and tauon and their masses are 105 and 1777 MeV respectively. Correspondingly there are three types or flavours of neutrinos called e, mu or tau neutrino that go respectively with the electron, muon or tauon in the beta decay as well as inverse beta decay interactions (See *Box* 5).

What is produced in the thermonuclear reactions in the Sun is the e neutrino. If some of the e neutrinos oscillate to the mu or the tau neutrinos on the way to the Earth, the depletion in the number detected on the Earth can be explained since the chlorine and gallium detectors cannot detect the mu or tau neutrinos. Just as the e neutrino produces an electron in the inverse beta decay process, the mu or tau neutrino has to produce a muon or a tauon respectively in the final state (See *Box* 6).

Box 6.

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



If we say that neutrinos have oscillated into some other flavour, we have to detect the neutrinos of those flavours too.This is precisely what the Sudbury Neutrino Observatory (SNO) achieved and thus finally solved the solar neutrino problem.

But since the energy of the solar neutrinos are limited to 14 MeV, the muon or tauon with the high masses of 105 and 1777 MeV cannot be produced in the inverse beta decay and so the neutrinos that have been converted into the mu or tau flavour through oscillation escape detection.

Although elastic scattering of neutrinos on electron which is used as the detecting mechanism in the Kamioka and SuperK water Cerenkov detectors can detect the converted mu or tau flavours also, 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 was a famous painting called 'The Cow and Grass'. But nothing except a blank convas 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.

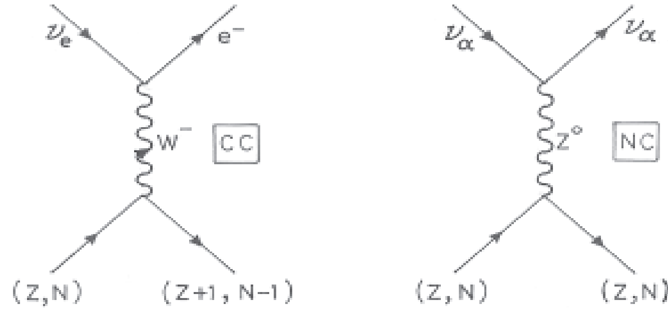
Our neutrino story so far is like that. We said thermonuclear reactions in the Sun must produce so many neutrinos. We did not see so many neutrinos, but then explained them away through oscillations.

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 (*Box* 7). There are two kinds of weak interaction processes. Beta decay in which a nucleus decays into another nucleus emitting a neutrino along with an electron as well as the related inverse beta decay in which a neutral neutrino colliding with a nucleus leads to a charged lepton and a different final nucleus are both charged current (CC) weak interaction processes. (Here charged lepton means electron, muon or tauon.) There is a second class of weak interaction known as neutral current

Box 7. CC and NC Reactions

ν_α stands for ν_e ν_μ or ν_τ. W^- is the charged weak boson while Z^0 is the neutral weak boson.



(NC) weak interaction in which the neutrino colliding with the nucleus excites or disintegrates it but remains as the neutrino in the final state. A low energy mu or tau flavoured neutrino will not cause the CC interaction in the nucleus as we already stated, but it can cause NC interaction. So if we design an experiment in which both the CC and NC modes are detected, although the CC mode will give only the number of e neutrinos, the NC mode will give the total number of e, mu and tau neutrinos. The total number detected will be a test of SSM independent of oscillations while the NC minus CC events will give the number that had oscillated away.

A huge two-in-one detector (BOREX) was proposed by Pakvasa and Raghavan but that has not materialized. The two-in-one detector based on deuteron in heavy water proposed by 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 neutrino breaks up the deuteron by CC and NC modes. While CC mode leads to two protons and an electron, NC mode leads to a neutron, a proton and a neutrino. The threshold of detection was again high like SuperK so that only the B-8 neutrinos were detected. Let us now straightaway go to the exciting results of SNO that came out in April 2002.

The CC mode gave the flux (million neutrinos per sq cm per sec) as 1.76 ± 0.11 while the NC gave 5.09 ± 0.65 in the same units. Thus we conclude that the flux of e + mu + tau neutrinos is 5.09 ± 0.65 while that of the e flavour alone is 1.76 ± 0.11. The difference 3.33 ± 0.66 is the flux of the mu + tau flavours. Hence oscillation is confirmed. Roughly two third of the e neutrinos have oscillated to the other flavours. Further, comparing with the SSM prediction of 5.05 ± 0.40, SSM also is confirmed. So at one sweep the SNO results confirmed both the SSM and neutrino oscillation.

In trying to verify the thermonuclear hypothesis experimentally through the detection of solar neutrinos, Davis and the other scientists made a discovery of fundamental importance, namely that the neutrinos have mass.

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.

3. Neutrino Oscillation

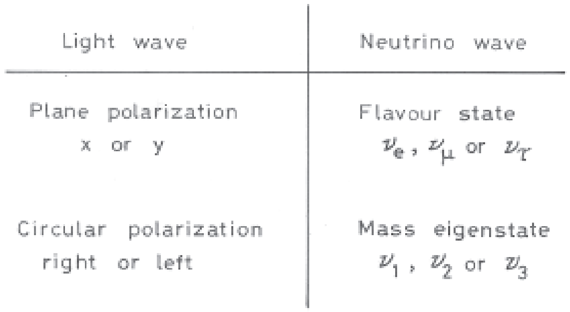
To understand neutrino oscillation, one must think of neutrino as a wave rather than a particle (remember quantum mechanics). Neutrino oscillation is a simple consequence of its wave property. Let us consider the analogy with light wave. Consider a light wave travelling in the z-direction. Its polarization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

In Quantum Mechanics, a particle behaves as a wave too and vice versa. To understand neutrino oscillation, think of neutrino as a wave.

Now consider plane polarized wave travelling through an optical medium. During propagation through the medium, it is important to resolve the plane polarized light into its circularly polarized components since it is the circularly polarized 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 polarizations travel with different velocities. And so when light emerges from the medium, the left and right circular polarizations have a phase difference proportional to the distance travelled. If we recombine the circular components to form plane polarized light, we will find the plane of polarization to have rotated from its initial orientation. Or, if we start with a polarization in the x-direction, 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 polarizations of the light wave are the three flavours (e, mu or tau) of the neutrino (See *Box* 8). When the neutrinos are produced in the 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 polarization 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 of neutrino wave will propagate as

Box 8. The Analogy between Light Wave and Neutrino Wave



Light wave	Neutrino wave
Plane polarization x or y	Flavour state ν_e, ν_μ or ν_τ
Circular polarization right or left	Mass eigenstate ν_1, ν_2 or ν_3

The fundamental importance of neutrino oscillation is that it implies that neutrinos have mass, since so far neutrinos were thought to be massless particles like photons.

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 mu component and tau component in addition to the e component it started with. This is what is called neutrino oscillation or neutrino flavour conversion through oscillation.

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 cannnot 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 sofar 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. Further, 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 become much more complex and richer in physics, but we shall not go into the details here. However it is important to mention two things. Hans Bethe redeemed himself for his earlier omission of neutrinos in his famous paper on the energy production in stars. This redemption came in the following way. After Wolfenstein pointed out the important effect of matter on the propagating neutrino and Mikheyev and 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 (including the present author) appreciated the beauty of MSW effect only after Bethe's paper came out.

Neutrinos are the most penetrating radiation known to us. Hence tomograhy of the Earth's interior by neutrino beams will be possible sometime in the future.

The second important thing 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 come!

4. Atmospheric Neutrinos

Solar neutrinos are MeV neutrinos. We now shift to GeV neutrinos. Cosmic rays, which are mostly protons, collide on the nitrogen and oxygen nuclei of the Earth's atmosphere and produce a large number of pions which ultimately decay into neutrinos and electrons. These are called atmospheric neutrinos. A pioneering experiment was done in India 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

The first detection of atmospheric neutrinos took place in India exactly 40 years ago, in the underground cosmic ray experiment in the Kolar Gold Field (KGF) mine.

(a few km thick) and hence one reaches the capability of detecting the cosmic ray produced neutrinos at those depths.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 mu-type neutrino. 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 mu neutrinos. In other words, the ratio R of mu-type to e-type must be 2. One could distinguish between the two types of neutrinos by observing either the electron or the muon that will be respectively emitted when the e neutrino or the mu neutrino has a CC interaction in the detector. Since the atmospheric neutrinos have energies in the GeV range, both the e-type and the mu-type of neutrinos can induce the CC reactions, in contrast to the solar neutrinos.

The Kamioka water Cerenkov detector in Japan could distinguish between the electron and the muon and thus measure the ratio R. It was found that the ratio was in fact 2 for the neutrinos coming in the downward direction, but it deviated considerably from 2 and was about 1 for those neutrinos coming in the upward direction which have obviously travelled through the 13,000 Km of the Earth diameter. Although the Kamioka detector and a few other detectors saw this anomaly in 1990, it required the SuperKamioka 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.

In the discovery of neutrino mass through oscillation, the atmospheric neutrino experiment of SuperK won the race, since this experiment depended on a ratio rather than on absolute flux.

5. Reactor Neutrinos

A fission reactor is a copious source of neutrinos (actually e-type antineutrinos). The very first experimental detection of neutrino was in fact made with reactor neutrinos. Fermi's theory of beta decay which was based on the existence of 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 doing it in 1954, thus ushering 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 delayed coincidence.(See *Box* 4)

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 upto 1 km. Although this was a null result, this played a crucial role in the global analysis of neutrino oscillations.

Even more recently, antineutrinos from a dozen power reactors in Japan were detected in a scintillation detector called KamLAND. Although the reactors were at various locations, they were all at about 180 km from the detector and at such a distance the antineutrinos must oscillate and this has been confirmed beautifully.

A new window on Geophysics was opened when KamLAND announced in July 2005 the first detection of geoneutrinos, ie, antineutrinos from the radioactive uranium and thorium ore buried in the bowels of the Earth.

6. Other Matters in Brief

A combined analysis of the solar, atmospheric and reactor neutrino data has led to a rough determination of the two differences of neutrino mass squares and the 3×3 mixing matrix, although there are still many uncertainties to be resolved. The mass-square differences are found to be very tiny: 0.002 and 0.00007 in units of electron-Volt (eV) squared.

Neutrinos from supernovae which are exploding stars is an important topic we have not discussed. In fact Bethe made fundamental contributions to the theory of supernova explosion and continued to work on it almost to the last day. Neutrinos in cosmology is another fascinating subject we have not touched.

Neutrino Physics has only started. There are still many questions to be answered. Although neutrinos are now known to be massive from the existence of neutrino oscillations, we do not know the values of the masses, 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. 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'.

There are many plans to start new neutrino laboratories all over the world. India was a pioneer in neutrino experiments. As we already pointed out, atmospheric neutrinos were first detected in the deep mines of KGF in 1965. It is planned to revive underground neutrino experiments in India. A multi-institutional Neutrino Collaboration has been formed with the objective of creating the India-based Neutrino Observatory (INO).

Suggested Reading

[1] **H A Bethe, Energy production in the stars, *Physical Review*, Vol.55, pp.434-456, 1939.**

[2] **J N Bahcall, *Neutrino Astrophysics*, Cambridge University Press, 1989.**

[3] **N G Cooper, Ed., *Celebrating the Neutrino*, Los Alamos Science, No.25 1997.**

[4] **D Indumathi, M V N Murthy and G Rajasekaran, Eds., Perspectives in Neutrino Physics, *Proceedings of Indian National Science Academy*, 76, January, 2004.**

More information on INO is available at the website http://www.imsc.res.in/~ino

Address for Correspondence
G Rajasekaran
Institute of Mathematical Sciences
Madras 600 113, India.
Email: graj@imsc.res.in