THE STORY OF THE NEUTRINO

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1.INTRODUCTION

In the recent past, two Nobel Prizes were given to Neutrino Physics. In 2002 Ray Davis of USA and Matoshi Koshiba of Japan got the Nobel Prize for Physics while last year (2015) Arthur McDonald of Canada and Takaaki Kajita of Japan got the Nobel Prize. To understand the importance of neutrino research it is neccessary to go through the story of the neutrino in some detail.

Starting with Pauli and Fermi, the early history of the neutrino is described culminating in its experimental detection by Cowan and Reines. Because of its historical importance 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 90-year-old thermonuclear hypothesis which states that the Sun and the stars are powered by thermonuclear fusion reactions and the attempts to prove this hypothesis experimentally.We go through Davis's pioneering experiments to detect the neutrinos emitted from these reactions in the Sun and 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 oscillation and neutrino mass was made.

We next describe the papellel story of cosmic-ray-produced neutrinos and how their study by SuperKamioka experiment in Japan won the race by discovering neutrino oscillations in 1998.

Many other important issues are briefly discussed at the end.

2.WHAT IS A NEUTRINO?

Neutrino is an elementary particle like electron. But unlike elecron which has a negative electric charge, it is neutral. Also, unlike electrons which are constituents of all atoms, neutrinos do not exist within atoms. But they are created through many processes all over the Universe in large numbers and are flying everywhere at almost the speed of light.

Every second more than 10^{12} neutrinos are passing through our body without affecting us in any way. Since the probability of neutrinos interacting with matter is negligible, they simply pass through all matter. Hence it requires huge detectors and sophisticated instruments to study them.

Until some years ago, neutrinos were regarded as massless particles like photons. But in 1998 neutrinos were discovered to have mass. This discovery is expected to lead to fundamental changes in our knowledge of physics and astronomy. Many more discoveries about neutrinos are yet to be made.

3.EARLY HISTORY OF NEUTRINO

After radioactivity was discovered by Becquerrel in 1897, many properties of radioactivity were revealed by the researches of a host of scientists including the famous ones Marie Curie and Ernest Rutherford. Among those, the so-called beta radioactivity turned out to be a puzzle. The electrons that came out in the beta activity did not come out with a single energy unlike the case of alpha and gamma activity where the alpha particle or the gamma photon emitted by a particular nucleus came with a single energy. The beta electrons had a continuous spectrum of energies. This seemed to contradict the principle of conservation of energy which is a cornerstone of Physics. Wolfgang Pauli in 1930 suggested a way to resolve this puzzle. If another unseen particle was emitted along with the electron, it could take away part of the energy and thus the principle of conservation of energy could be saved. This was Pauli's suggestion.

Although neutrino was born in the mind of Pauli, it was Enrico Fermi who made neutrino the basis of his famous theory of beta decay in 1932 and showed how in the beta decay of a nucleus an electron and a neutrino are simultaneously created [1]. It is this that remained as the basic theory of the decays of all elementary particles for more than 40 years. It was also Fermi who christened the particle as 'Neutrino'.

In the subsequent decades beta decays of many atomic nuclei were experimentally studied. All of them were in beautiful agreement with Fermi's theory and hence it was clear to theoretical physicists atleast that Pauli's neutrinos were indeed emitted in beta decay. But Cowan and Reines did not agree. If neutrinos exist, their existence must be experimentally proved, they said. And they proved it in 1954.

Before we describe their experiment, it is neccessary to explain beta decays of nuclei.

4. BETA DECAYS AND THE COWAN-REINES EXPERIMENT

Every atomic nucleus contains Z number of protons and N number of neutrons. For example, the nucleus of the Hydrogen atom is a single proton. Helium nucleus contains 2 protons and 2 neutrons. Uranium nucleus contains 92 protons and 146 neutrons. Many nuclei undergo beta decay spontaneously. The nucleus (Z,N) which contains Z protons and N neutrons emits an electron (e^-) and an antineutrino $\bar{\nu}_e$ and becomes the nucleus (Z+1,N-1) containing Z+1 protons and N-1 neutrons. This is shown in the first line of Fig 1. In the same way, neutron (n) decays and becomes a proton as shown in line 2.

If we transfer the antineutrino from the right side of the first line to the left side, it will be a neutrino. As shown in line 3, this then denotes the reaction in which a neutrino ν_e collides with a nucleus (Z,N) and the result is another nucleus (Z+1, N-1) and an electron e^-. This is sometimes called inverse beta decay and it is through such reactions experimental physicists detected neutrinos.

In line 4, nucleus (Z,N) emits a positron e^+ and a neutrino ν_e and becomes the nucleus (Z-1, N+1). Here, if we transfer the neutrino to the left side, it will be an antineutrino $\bar{\nu}_e$ and we will have a reaction of the antineutrino (shown in line 5). As an example, an antineutrino and a proton collide and become a positron and a neutron (line 6). It is this reaction that Cowan and Reines used to prove the real existence of the neutrino (actually the antineutrino).

Every nuclear reactor is a copious source of antineutrinos. How? When nuclei such as Uranium fission in the nuclear reactor, a variety of radioactive nuclei are produced. Many of them undergo beta decay and emit antineutrinos. Cowan and Reines used a hydrogenous material as their detector. Hydrogen nucleus is a proton. If the antineutrino from the reactor interacts with the proton, a positron and a neutron are produced, as we already saw (line 6 of Fig 1). Reines and Cowan proved the appearance of the positron and neutron in their detector placed near the nuclear reactor. Thus the emission of antineutrinos from the nuclear reactor was experimentally proved by Cowan and Reines in 1954. Reines received the Nobel Prize in 1995. Cowan had passed away before that.

There are two interesting episodes connected to the Cowan-Reines experiment. In that period (1945-55) many nuclear bomb tests were being conducted. In the explosion of the nuclear bomb also, Uranium nucleus fissions and antineutrinos are produced. Cowan and Reines had planned to catch those antineutrinos, but were prevented from pursuing that dangerous venture. They then changed their plan and went to the Savannah River Reactor (USA) to do their experiment and succeeded. Pauli had apparently sent a cable telegram to the Committee which was to decide on the sanction of financial support for the Cowan-Reines experiment, saying that "his particle" cannot be detected by anybody and so asking the Committee not to support such an experiment. However that telegram did not reach the Committee in time; support was given and the antineutrino was caught in the experiment!

5. NEUTRINOS FROM THE SUN

It is the Sun that is giving us light and heat. Without it, life on Earth is impossible. How does Sun produce its energy and continue to shine for billions of years? 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 atomic nucleus and the tremendous amount of energy locked up in the nucleus, Eddington 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 Bethe,the Master Nuclear Physicist, analysed all the relevant facts and solved the problem completely in 1939. A year earlier,Weisszacker had given a partial solution.

Bethe's paper is a masterpiece[2]. 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. And it is Fermi's theory that Bethe used in his work. So it is rather inexplicable why he 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 in Astronomy and Astrophysics written in the 40's and 50's do not mention neutrinos! This was unfortunate,since we must realize that,inspite 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.

The basic process of thermonuclear fusion in the Sun and stars is four protons (which are the same as Hydrogen nuclei) combining into a Helium nucleus and releasing two positrons,two neutrinos and 26.7 MeV of energy.

$$p + p + p + p \rightarrow He^4 + e^+ + e^+ + \nu_e + \nu_e$$

This can be regarded as the most important reaction for all life, for without it Sun cannot shine and there can be no life on Earth!

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 and the pp-chain. 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.

We shall not go into details here [3] except noting that both in the carbon cycle and the pp-chain,the net process is the same as what was mentioned above, namely the fusion of four protons to form alpha particle with the emission of two positrons and two neutrinos.

It is these thermonuclear fusion reactions that are responsible for the Sun and the stars continuing to shine for billions of years. This fact remained as a theoretical fact for many decades although it was accepted as generally correct by scientists. So even Nobel Prize was given to Bethe in 1967.

The only way to prove Bethe's theory is to detect the neutrinos coming from the Sun.

It is easy 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. These many solar neutrinos are passing through our body and the Earth.

6. THE DAVIS EXPERIMENT

About 50 years ago Ray Davis started his pioneering experiments to detect the solar neutrinos. His experiment was based on the inverse beta decay:

$$\nu_e + Cl^{37} \rightarrow e^- + Ar^{37}$$

Chlorine-37 absorbs the solar neutrino to yield Argon-37 and an electron. (See Fig 1 and its explanation 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 Chlorine-37 atoms in the fluid were converted into Argon-37 atoms by the above reaction. The fluid was periodically purged with Helium gas to remove the Argon-37 atoms which were then counted by means of their radioactivity. Davis continued his experiment for almost 30 years and the result was that about one neutrino in three days was caught in his experiment.

Two points must be noted. In three days billions of neutrinos fall on Davis's tank, but only one among them reacted with Chlorine-37 and got caught. All others escape without any interaction, thus showing how tiny is the probability of interaction of a neutrino. The experiment also proves the extraordinary capability of Davis in counting radioactive atoms. If you colour one grain of sand red and mix it in the sand of Sahara desert, can one find that red grain of sand? The achievement of Davis is comparable to that.

Although solar neutrinos were detected by Davis, a new puzzle appeared. Actually Davis detected only about a third of the solar neutrinos that must have been detected in his tank. What is the reason for this discrepancy between the theoretical number of solar neutrinos that must be detected in Davis's detector and the actual number detected? Are the thermonuclear fusion hypothesis and Bethe's theory based on it wrong? This became known as the solar neutrino puzzle and the puzzle lasted for many years.

7. KAMIOKA AND SUPERKAMIOKA

A few other experiments were undertaken in the attempt to resolve the solar neutrino puzzle. The most important one among them was the

Kamioka experiment in Japan led by Matoshi Koshiba.

One must also note that 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 which was a passive detector,the Kamioka water Cerenkov detector is an active real time detector. Solar neutrino kicks out an electron in the water molecule by 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 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 ratio of the measured solar neutrino flux to the predicted flux was about 0.5, thus confirming the solar neutrino puzzle.

There is a difficulty in resolving the solar neutrino puzzle. To understand that, we have to know more details about the Sun.

8. STANDARD SOLAR MODEL AND THE GALLIUM EXPERIMENTS

In the Sun,the dominant thermonuclear fusion process is the pp-chain.Although the 70 billion neutrinos per square centimeter per sec as the total number of solar neutrinos falling on the Earth 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 about the interior of the Sun.

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 [3], 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. Most of the neutrino detectors detect only the tiny high-energy branch of the spectrum.

While the dominant low-energy neutrino flux is basically determined by the solar luminosity,the flux of the high-energy 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 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. 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 dependance 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 dependance on the kinetic energy of the colliding charged particles.

The detection threshold in Davis's experiment was 0.8 MeV and thus only the high-energy 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.

The energy threshold of the Kamioka and SuperKamioka detectors was about 7 MeV and so only the high-energy part of the neutrino spectrum was being detected.

The next input came from the gallium experiments. The high-energy 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 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 low-energy branch extending upto 0.42 MeV.Actually two gallium detectors were mounted,called SAGE and GALLEX and both succeeded in detecting the pp 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.

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 crosssections do lead to a large uncertainty in the SSM prediction. But astrophysicists led by John 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 low-energy 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 something else is the reason for R being less than unity and that is neutrino oscillation.

9. THREE KINDS OF NEUTRINOS

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 eneutrino (ν_e), mu neutrino (ν_μ) or tau neutrino (ν_τ) that are respective companions of electron,muon or tauon (See Fig 2). Just is electron and eneutrino are emitted in beta decay, in the processes involving muon or taon, muneutrino or tauneutrino will appear.

What is produced in the thermonuclear reactions in the Sun is the antielectron (positron) and eneutrino. This eneutrino produced an electron when it converted the Chlorine-37 nucleus in Davis's detector into an Argon-37 nucleus:

$\nu_e + Cl^{37} \rightarrow e^- + Ar^{37}$ (1)

If some of the eneutrinos oscillate to the muneutrinos or the tauneutrinos on the way to the earth, the reactions in Davis's detector must be

$\nu_\mu + Cl^{37} \rightarrow \mu^- + Ar^{37}$ (2)

or

$\nu_\tau + Cl^{37} \rightarrow \tau^- + Ar^{37}$ (3)

Just as the eneutrino produces an electron in the inverse beta decay process, the muneutrino or the tauneutrino has to produce a muon or a tauon respectively in the final state. 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. According to Einstein's famous equation

$E = mc^2$

it is energy E which is converted into mass m. So the neutrinos that have been converted into the mu or tau flavour through oscillation escape detection in the Chlorine and Gallium experiments.

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 convass 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.

10. TWO-IN-ONE EXPERIMENT (SNO)

The beta decay and inverse beta decay processes that we have described so far are charge-changing (CC) weak interaction processes. Another kind of weak interaction, known as charge-nonchanging or neutral current (NC) weak interaction was discovered in 1973. These two kinds of processes are shown below:

$\nu_e + (Z, N) \to (Z + 1, N - 1) + e^-$ (CC)

$\nu + (Z, N) \to (Z, N)^* + \nu$ (NC)

In the CC process eneutrino changes into electron. Neutrino does not have charge while electron does have charge. So charge of the particle changes in the process and hence CC. The nucleus also changes from (Z,N) to (Z+1, N-1) and so its charge changes. But in the NC process, neutrino remains as neutrino. The nucleus (Z,N), without changing its charge, either gets exited to a higher energy state or disintegrates. We have denoted such a state of the nucleus as $(Z, N)^*$ in the NC reaction above.

The important point is that the solar eneutrinos that oscillated into the mu type or the tao type cannot undergo the appropriate CC process as we already explained. But since the NC process does not create the heavier muon or taon, they can undergo the NC process. So if we design an experiment in which both the CC and NC modes are detected, and if the number of neutrinos involved in NC reactions is found to be larger than those in CC reactions, oscillation will be proved.

While the CC mode will give the number of eneutrinos, the NC mode will give the total number of e, mu and tau type of neutrinos. The total number detected will be a test of SSM independant of oscillations while the NC minus CC events will give the number that had oscillated away.

This is the 'two-in-one" experiment. A huge two-in-one detector based on Boron called BOREX was proposed by Sandip Pakvasa and Raju Raghavan (who passed away in 2011), but that has not materialized.The two-in-one detector based on deuteron in heavy water proposed by Chen was constructed at the Sudbury Neutrino Observatory (SNO), Canada and it finally solved the solar neutrino puzzle. SNO uses 1000 tons of heavy water borrowed from the Canadian Atomic Energy Commission.

Just as water is made of H_2O molecules, heavy water is made of D_2O molecules. The nucleus of the heavy hydrogen D is made up of one proton and one neutron. Solar neutrino breaks up the deuteron D 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.

$\nu_e + D \rightarrow p + p + e^-$ (CC)

$\nu + D \rightarrow p + n + \nu$ (NC)

The threshold of detection was again high like SuperK so that only the high energy 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. (The numbers are in millions rather than in billions since the threshold of detection was again high like in SuperK so that only the high-energy neutrinos were detected.) 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 eneutrinos 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 based on the thermonuclear fusion hypothesis and neutrino oscillation.

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 scientists have made a discovery of fundamental importance, namely that the neutrinos have mass. Only if they have mass, they can oscillate.

11. 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 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.

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.

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 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 3x3 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. After Wolfenstein calculated 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. One may comment that Bethe redeemed himself for his earlier omission of neutrinos in his famous paper on the energy production in stars.

We next go to the cosmic-ray-produced neutrinos since their study and its interplay with solar neutrino research constitute a fascinating chapter in the story of the neutrino.

12. COSMIC-RAY-PRODUCED OR ATMOSPHERIC NEUTRINOS

Cosmic Rays were discovered around the year 1900. They are mostly very energetic protons. They are created in many parts of the Universe and are flying in all directions everywhere. They fall on Earth too. Since Earth is surrounded by atmosphere, these protons collide on the nitrogen or oxygen nuclei of the atmosphere and in these collisions many kinds of elementary particles are created. All these move in the direction of the Earth. Fig 3 shows such a cosmic-ray shower. Many elementary particles such as muon (μ), pion (π), and Kaon (K) were originally discovered in cosmic ray reasearch only. As seen from the Figure, all these particles decay and give rise to neutrinos. They are cosmic-ray produced neutrinos although they are generally called atmospheric neutrinos.

Homi Jahangir Bhabha who founded the Tata Institute of Fundamental Research in Mumbai was well-known for cosmic ray research. Around 1950, he suggested to B V Sreekantan that cosmic ray research must be conducted in Kolar Gold Field (KGF) mine which is one of the deepest mines in the world. His idea was to measure the flux of cosmic ray particles as we go down the depth of one or two kilometers below the Earth and verify experimentally whether the penetrating component of the cosmic rays was composed of muons alone (as he had concluded in his earlier theoretical research) or whether there was any other particle.

Sreekantan, Ramanamurthy and Naranan followed Bhabha's suggestion and thus started the pioneering KGF experiments and the experiments continued for more than two decades. The scientists determined how the muon flux decreased as a function of the depth. When the experiments were continued at greater and greater depths, at a certain depth the number of the muons detected became zero. At that depth (which was about 2 kilometer from the surface of the Earth) all the muons are absorbed by the rock above, but neutrinos are not absorbed and hence could be detected without any disturbance from other particles such as muons. The scientists suceeded in detecting these neutrinos. This happened in the year 1965. This was the first detection of cosmic-ray-produced neutrinos in the world. The credit for this achievement goes to the Tata Institute of Fundamental Research and two other collaborating institutions Durham University, UK and Osaka University, Japan. Last year 2015 was the Golden Jubilee Year of this milestone in the story of the neutrino.

The atmospheric neutrino research that started in India progressed further especially in Japan and brought great succeess to the Japanese physicists. We have already described how the Kamioka and SuperKamioka experiments succeeded in catching the solar neutrinos. The same experiments caught the atmospheric neutrinos also. Further study led to another discovery which we describe now.

The pion born from cosmic rays decays into a muon and a muneutrino. Then the muon also decays into an electron, an eneutrino and a muneutrino. The decay of the Kaon also leads to same results. Hence as shown in Fig 3, the number of muneutrinos reaching the Earth is twice the number of eneutrinos. In the Kamioka experiments, it was possible to distinguish the two kinds of neutrinos. Since the cosmic ray protons had a very high energy, about 1000 MeV, the neutrinos born from them have very high energy and so can create the muons of 107 MeV. The muneutrinos colliding with the nuclei in the detector produce muons and eneutrinos produce electrons. Since muons and electrons emit different kinds of Cerenkov light, the Kamioka and SuperK experimenters succeeded in counting the number of colliding muneutrinos and eneutrinos separately.

The underground SuperK detector and the directions in which neutrinos arrive at the detector are shown in Fig 4. The sky and atmosphere surround the Earth in all directions and so the neutrinos arrive from all directions. In the downward direction, the ratio of muneutrinos to eneutrinos was experimentally shown to be 2 as expected. But this ratio gradually decreased from 2 as the direction changed and became unity for the upward moving neutrinos. Although Kamioka detector and a few other detectors saw this anomaly in 1990, it required the bigger SuperK detector with its superior statistics to establish the effect in 1998.

About half of the upward moving muneutrinos have disappered. How? The maximum height of the atmosphere is about 20 kilometer. So neutrinos coming downwards from above travel only a few kilometers and reach the detector without oscillation. Neutrinos coming upwards have to cross a distance of 13,000 kilometers which is Earth's diameter and undergo oscillation. Half of the muneutrinos oscillate to the tauneutrinos. Although the cosmic-ray produced neutrinos have high enough energy to create the muon, their energy is not sufficient to create the taon of mass 1777 MeV. So the tauneutrinos escape undetected. Thus the SuperK experiment discovered the oscillation of cosmic-ray produced neutrinos.

13. THE NOBEL PRIZES: SOLAR AND ATMOSPHERIC NEUTRINOS

One may say that it is in the Davis experiment on solar neutrinos that neutrino oscillation and neutrino mass were discovered first. However it was not possible to accept these conclusions as firm on the basis of the Davis experiment. For, as we mentioned earlier the question as to whether the flux of the higher energy neutrinos from the Sun was calculated correctly could not be settled without any doubt. This doubt was completely removed only by the results of the two-in-one experiment of SNO, since the inference of neutrino oscillation from SNO results was completely independant of the calculation of the solar neutrino flux.

SNO results came out only in 2002. Much before that, in 1998, SuperK discovered the oscillations of cosmic-ray-produced neutrinos. Their discovery concerned the ratio of muneutrinos to eneutrinos and hence did not depend on the uncertainties of calculated fluxes of the neutrinos produced by cosmic rays. Hence it was accepted that the discovery of neutrino oscillation and neutrino mass by SuperK in cosmic-ray-produced neutrino experiments was free from doubts of the kind that plagued the interpretation of Davis and SuperK experiments on solar neutrinos. In the race for the discovery of oscillations experiments on cosmic-ray-produced neutrinos won over those on solar neutrinos.

In 2002, Nobel Prize was given to Ray Davis who pioneered solar neutrino research, was the first to detect solar neutrinos and continued the experiments for more than 30 years and Matoshi Koshiba who was the leader of the Kamioka and SuperK experiments that detected solar neutrinos, cosmic-ray-produced neutrinos and Supernova neutrinos. The Nobel Prize of 2015 was given to Arthur McDonald who was the leader of SNO which proved thermonuclear fusion as the source of solar energy and firmly established oscillation of solar neutrinos and to Takaaki Kajita who was the leader of SuperK that discovered the oscillations of cosmic-ray- produced neutrinos.

14. NEUTRINO MASSES AND MIXING

As we already mentioned, nuclear reactors produce antineutrinos copiously. High energy protons from particle accelerators produce pions whose decays ultimately lead to neutrinos. This is in fact the same process as in case of cosmic-ray protons which we mentioned earlier.

Solar neutrinos, atmospheric neutrinos, reactor neutrinos and accelerator neutrinos – many experiments on all these have been done and considerable amout of information on neutrino oscillations have been learnt. Most importantly, the mass-differences between the three kinds of neutrinos have been determined and they are very very tiny:

$$m_2^2 - m_1^2 = 0.00007 eV^2$$

$$|m_3^2 - m_2^2| = 0.002 eV^2$$

Note one of the mass difference is known only in magnitude and its sign has yet to be determined and so the ordering of the three mass levels is not yet known.

Oscillation experiments give only mass differences. To determine the mass itself a different knid of experiment has to be done. From the precision experimental study of the continuous energy distribution of the electrons emitted in the beta decay of Tritium (heavy Hydrogen), an upper limit of 2.2 eV for the neutrino mass or masses has been determined. So, all the three neutrino masses are clustered close to each other at a value smaller than 2.2 eV. Amomg all the massive elementary particles, electron has the lowest mass 0.5 MeV. Neutrino masses are a million times smaller. But many secrets of the Universe are hidden in this tiny number.

As a culmination of hundred years of fundamental research a theory called the Standard Model of High Energy Physics [4] has been shown to be the basis of almost All of physics except gravity. But according to this theory neutrinos are massless. Hence the importance of the discovery that neutrinos have mass. Neutrino mass may be the portal to go beyond Standard Model.

The oscillation experiments also determined the 3x3 mixing matrix that tells us how the three massive neutrinos are superposed to give the three flavours e, μ, τ of neutrinos. This unitary matrix is characterized by three angle parameters and a phase. The values of the three angles as determined by the oscillation experiments [5] are

$\theta_{12} = 30 degrees$
$\theta_{23} = 45 degrees$
$\theta_{31} = 9 degrees$

The phase however is not yet determined. This phase is very important since it signals matter-antimatter asymmetry which in turn can play an important role in the evolution of the Universe as pointed out below.

15. CONTINUING STORY

There are many more things in the neutrino story. We shall describe them briefly.

Generally there is an antiparticle for every particle. This is a Law of Nature which is a consequence of combining quantum mechanics with relativity and was discovered by Dirac. Positron is the antiparticle of electron. Their electric charges are equal in magnitude but opposite in sign. However, when the electric charge is zero as is the case for neutrino, its antiparticle, namely the antineutrino could be the same as the neutrino itself. If this is true, the particle is called a Majorana particle, named after Majorana who envisaged such a possibility. A particle whose antiparticle is different, such as the electron is called a Dirac particle. Is neutrino a Majorana particle? [6] This is the most important question in Neutrino Physics and this question can be answered only by the "neurinoless double beta decay experiment". These experiments are going on, but have not yet yielded a definitive answer.

Cosmologists have found good evidence that the Universe was born 14 billion years ago in a gigantic explosion called the Big Bang. At that point, the Universe must have contained equal number of particles and antiparticles. However there are only particles now. All the atoms in the Universe are made of protons, neutrons and electrons only. What happened to the antiprotons, antineutrons and positrons? How did they disappear? How was the matter-antimatter symmetry that existed at the beginning of the Universe destroyed? This is an important cosmological puzzle. The key to solving this puzzle is contained in the neutrino. If neutrino and antineutrino can be proved to be the same and if the phase in the mixing matrix (see above) is proved to be nonzero, this puzzle can be answered. Hence, neutrino plays an important role in cosmological research.

Supernova explosion is the end stage of most of the stars. Most of the energy of the explosion is released through the neutrinos that are emitted in a very large number. The neutrinos emitted in the so-called Supernova 1987-a were detected in the SuperK detector. This was one of the reasons for the Nobel Prize given to Koshiba in 2002 since this was the first time neutrinos from outside the solar system were first detected on the Earth and supernova neutrino research was thus initiated.

Ultrahigh energy neutrinos with energy greater than 10^{12} eV coming from outer space have been detected in the year 2013. This was achieved by using ice as a detector in the Antartica Continent near the South Pole. The size of this ice detector is one kilometer in length, one kilometer in breadth and one kilometer in height and it is called Ice Cube.

Radioactive Uranium and Thorium ores lying buried in the deep bowels of the Earth emit neutrinos. These geoneutrinos have been detected in the KamLAND detector in Japan and the BOREXINO detector of the Gran Sasso laboratory in Italy. Through this, one can map where and at what depths Uranium and Thorium ores lie and this knowledge will be used in Geochronology. Thus a new window on Earth Science has been opened by neutrino research

The bulk of the low-energy neutrinos constituting more than 90 percent of the solar neutrinos which had eluded detection have now been detected by the BOREXINO detector. The measured flux is in very good agreement with SSM.

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 which may even lead to the prediction of earthquakes in future. This requires our mastery of neutrino technology. But neutrino technology will be mastered and neutrino tomography will come.

Efforts are going on all over the world to create new underground laboratories for neutrinos. As already mentioned, India was a pioneer in neutrino research. The cosmic-ray-produced neutrinos first detected in KGF in India in 1965 led to two Nobel Prizes for the Japanese physicists. But the KGF mines were closed in 1995. To recover this lost initiative the India-based Neutrino Observatory (INO) has been planned [7]. The underground laboratory will be created in a huge cavern to be dug out in a mountain in Theni District near Madurai and the main Centre of INO will be built in Madurai City. In the first stage, a neutrino oscillation experiment using atmospheric neutrinos will be performed in a gigantic 50,000 ton magnetised iron detector which will be mounted inside the underground laboratory [7].

MILESTONES IN THE NEUTRINO STORY

1930 Birth of Neutrino: Pauli
1932 Theory of beta decay, "Neutrino" named: Fermi
1954 First detection of neutrino: Cowan and Reines
1964 Discovery of muneutrino: Lederman, Schwartz and Steinberger
1965 Detection of atmospheric neutrino: KGF
1970 Start of the solar neutrino experiment: Davis
1987 Detection of neutrinos from supernova: SuperKamioka
1998 Discovery of neutrino oscillation and mass: SuperKamioka
2001 Discovery of tauneutrino: DONUT
2002 Solution of the solar neutrino puzzle: SNO
2005 Detection of geoneutrinos: KamLAND
2013 Detection of ultra high energy neutrinos from space: Ice Cube

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[7] www.ino.tifr.res.in/ino

$$(Z, N) \rightarrow (Z+1, N-1) + e^- + \bar{\nu}_e \quad (\beta^- \text{ decay}) \tag{1}$$

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (\beta^- \text{ decay of n}) \tag{2}$$

$$\nu_e + (Z, N) \rightarrow (Z+1, N-1) + e^- \quad (\text{inverse } \beta^- \text{ decay}) \tag{3}$$

$$(Z, N) \rightarrow (Z-1, N+1) + e^+ + \nu_e \quad (\beta^+ \text{ decay}) \tag{4}$$

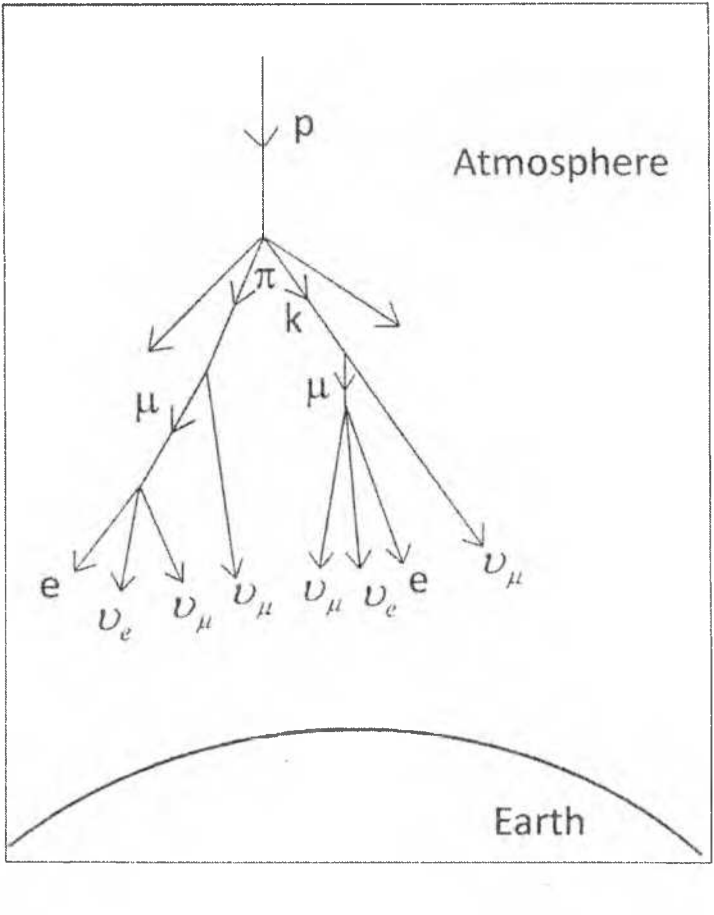
$$\bar{\nu}_e + (Z, N) \rightarrow (Z-1, N+1) + e^+ \quad (\text{Inverse } \beta^+ \text{ decay}) \tag{5}$$

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (\text{Cowan-Reines reaction}) \tag{6}$$

படம் 1

$$\boxed{\begin{pmatrix} \upsilon_e \\ e \end{pmatrix} \quad \begin{pmatrix} \upsilon_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \upsilon_\tau \\ \tau \end{pmatrix}}$$

படம் 2


p
Atmosphere
π
k
μ
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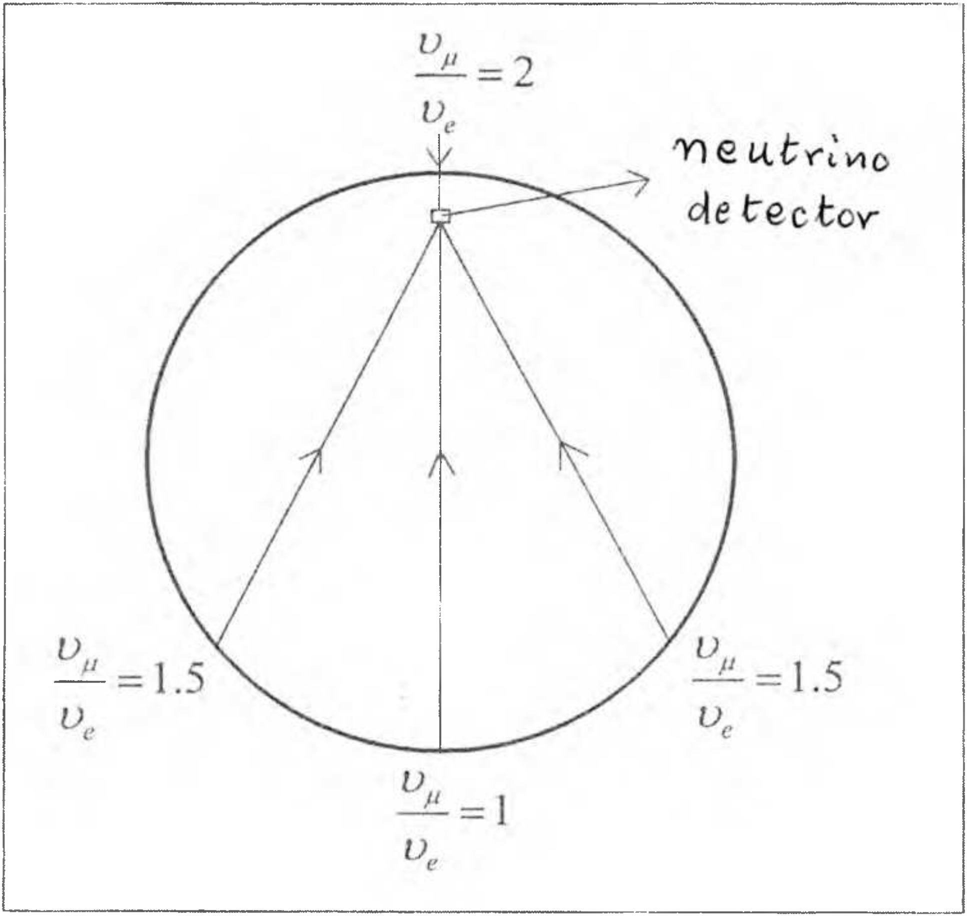
υ_μ
υ_μ
υ_μ
υ_e
e
υ_μ
Earth

படம் 3


$\frac{\upsilon_\mu}{\upsilon_e} = 2$
neutrino detector
$\frac{\upsilon_\mu}{\upsilon_e} = 1.5$
$\frac{\upsilon_\mu}{\upsilon_e} = 1.5$
$\frac{\upsilon_\mu}{\upsilon_e} = 1$

படம் 4