PHENOMENOLOGY OF SOLAR NEUTRINOS BEYOND LMA

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CERTIFICATE

This is to certify that Mr. Baljit Kumar, Roll No. 30704002 has worked on this thesis report as a partial fulfillment for award of the degree of **MASTERS OF SCIENCE** in physics. I certify that the matter embodied in this report is of candidate's own record and not submitted to any other university in any part or full form for the award of such a degree.

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1.1.The neutrino: A Brief History.

Neutrio , the byproduct of thermo nuclear fusion reaction in the sun was postulated in 1930 by Wolfgang Pauli [1]. In 1933 Enricho fermi in his formulation of the theory of β decay [2] named it as the little neutron or neutrinos . In 1945 B. Pontecorvo [3] put forward the idea that neutrino could be detected via the reaction $^{37}Cl\ (\nu,e)^{37}Ar$ .In 1954, R.Davis used this radioactive technique to detect Ar. In 1956, Cowans and Rienes [4,5] discovered the antineutrino through the reaction

$$v_e + p \rightarrow e^+ + p$$

In 1943, S.Sakata and T. Inoue [6] anticipated the istence of existence of a second neutrino, the muon neutrino which was detected by G.Danby et al.[7] 1962. M.L. Perl et al.[8]. Discovered the charged lepton and the corresponding tau neutrino were detected in 2000.

From the various conservation laws ,it is concluded that the neutrinos are electrically neutral and have spin half. In the standard model, neutrinos have zero rest mass. But we do not have any physical need for the neutrino mass to be identically zero.

After Cowan and Rienes Experiments in 1956, it was established that ν and $\bar{\nu}$ are different particles and thereis no fundamental property which distinguish ν from $\bar{\nu}$:all $\bar{\nu}$ have spin vector parallel to momentum vector, while all ν have spin vector opposite to momentum vector.This property is called helicity and is defined as

$$h=\frac{s.p}{|s.p|}$$

which has a value of +1 for $\overline{\nu_e}$ and -1 for ν_e.

Neutrinos are similar to the more familiar electron, with one crucial difference: neutrinos do not carry electric charge. Because neutrinos are electrically neutral, they are not affected by the electromagnetic forces which act on electrons. Neutrinos are affected only by a "weak" sub-atomic force of much shorter range than electromagnetism, and are therefore able to pass through great distances in matter without being affected by it. If neutrinos have mass, they also interact gravitationally with other massive particles, but gravity is by far the weakest of the four known forces.

Three types of neutrinos are known; there is strong evidence that no additional neutrinos exist, unless their properties are unexpectedly very different from the known types. Each type or "flavor" of neutrino is related to a charged particle (which gives the corresponding neutrino its name). Hence, the "electron neutrino" is associated with the electron, and two other neutrinos are associated with heavier versions of the electron called the muon and the tau (elementary particles are frequently labelled with Greek letters, to confuse the layman). The table below lists the known types of neutrinos (and their electrically charged partners).

Neutrino		N_e		N_m		N
Charged Partner		electron (e)		Muon(μ)		Tau(τ)

1931 - A hypothetical particle is predicted by the theorist Wolfgang Pauli. Pauli based his prediction on the fact that energy and momentum did not appear to be conserved in certain radioactive decays. Pauli suggested that this missing energy might be carried off, unseen, by a neutral particle which was escaping detection.

1934 - Enrico Fermi develops a comprehensive theory of radioactive decays, including Pauli's hypothetical particle, which Fermi coins the neutrino (Italian: "little neutral one"). With inclusion of the neutrino, Fermi's theory accurately explains many experimentally Observed results.

1959 - Discovery of a particle fitting the expected characteristics of the neutrino is announced by Clyde Cowan and Fred Reines (a founding member of Super-Kamiokande; UCI professor emeritus and recipient of the 1995 Nobel Prize in physics for his contribution to the discovery). This neutrino is later determined to be the partner of the electron.

1962 - Experiments at Brookhaven National Laboratory and CERN, the European Laboratory for Nuclear Physics make a surprising discovery: neutrinos produced in association with muons do not behave the same as those produced in association with electrons. They have, in fact, discovered a second type of neutrino (the muon neutrino).

1968 - The first experiment to detect (electron) neutrinos produced by the Sun's burning (using a liquid Chlorine target deep underground) reports that less than half the expected neutrinos are observed. This is the origin of the long-standing "solar neutrino problem." The possibility that the missing electron neutrinos may have transformed into another type (undetectable to this experiment) is soon suggested, but unreliability of the solar model on which the expected neutrino rates are based is initially considered a more likely explanation.

1978 - The tau particle is discovered at SLAC, the Stanford Linear Accelerator Center. It is soon recognized to be a heavier version of the electron and muon, and its decay exhibits the same apparent imbalance of energy and momentum that led Pauli to predict the existence of the neutrino in 1931. The existence of a third neutrino associated with the tau is hence inferred, although this neutrino has yet to be directly observed.

1985 - The IMB experiment, a large water detector searching for proton decay but which also detects neutrinos, notices that fewer muon-neutrino interactions than expected are observed. The anomaly is at first believed to be an artifact of detector inefficiencies.

1985 - A Russian team reports measurement, for the first time, of a non-zero neutrino mass. The mass is extremely small (10,000 times less than the mass of the electron), but subsequent attempts to independently reproduce the measurement do not succeed.

1987 - Kamiokande, another large water detector looking for proton decay, and IMB detect a simultaneous burst of neutrinos from Supernova 1987A.

1988 - Kamiokande, another water detector looking for proton decay but better able to distinguish muon neutrino interactions from those of electron neutrino, reports that they observe only about 60% of the expected number of muon-neutrino interactions

1989 - The Frejus and NUSEX experiments, much smaller than either Kamiokande or IMB, and using iron rather than water as the neutrino target, report no deficit of muon-neutrino interactions.

1989 - Experiments at CERN's Large Electron-Positron (LEP) accelerator determine that no additional neutrinos beyond the three already known can exist.

1989 - Kamiokande becomes the second experiment to detect neutrinos from the Sun, and confirms the long-standing anomaly by finding only about 1/3 the expected rate.

1990 - After an upgrade which improves the ability to identify muon-neutrino interactions, IMB confirms the deficit of muon neutrino interactions reported by Kamiokande.

1994 - The Kamiokande and IMB groups collaborate to test the ability of water detectors to distinguish muon- and electron-neutrino interactions, using a test beam at the KEK accelerator laboratory. The results confirm the validity of earlier measurements. The two groups will go on to form the nucleus of the Super-Kamiokande project.

1997 - The Soudan-II experiment becomes the first iron detector to observe the disappearance of muon neutrinos. The rate of disappearance agrees with that observed by Kamiokande and IMB.

1997 - Super-Kamiokande reports a deficit of cosmic-ray muon neutrinos and solar electron neutrinos, at rates agreeing with measurements by earlier experiments.

1998 - The Super-Kamiokande collaboration announces evidence of non-zero neutrino mass at the Neutrino '98 conference.

1.2. THE SOLAR NEUTRINO EXPERIMENTS

Due to very small cross section for neutrino interaction,it is very difficult to detect neutrinos even with very huge detectors.In the detection of solar neutrinos ,the background poses a serious problem as it greatly modifies the actual neutrino flux. To overcome this problem,the solar neutrino detectors are situated deep underground to reduce the background flux as far as possible.brief description of some solar neutrino experiment are given as follows:

The Homestake Experiment (^{37}Cl experiment)

In this experiment ,the neutrinos detection is based on the production of radioactive ^{37}Ar via the reaction

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar \qquad E_{th}=0.814 \text{ MeV}$$

The 0.8 MeV threshold energy permits the detection of all the major solar neutrinos except the basic pp neutrinos. The event rate predicted by the SSM for ^{37}Cl detection is $7.6^{+1.3}_{-1.1}$ SNU whereas the observed rate is 2.56±0.226 SNU.

The Gallium Experiment

The two radiochemical experiments GALLEX and SAGE use the reaction

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ga \qquad E_{th}=0.233 \text{ MeV}$$

The low threshold energy makes possible the detection of majority of pp neutrons. The `total capture rate predicted by SSM for ^{71}Ga detector is 128^{+9}_{-7} SNU. However , the experimentally measured solar neutrino flux by the GALLEX detector is $77^{+7.545}_{-7.780}$ SNU and that measured by the SAGE detector is$70.8^{+6.463}_{-6.105}$ SNU.

The Kamiokande Experiment

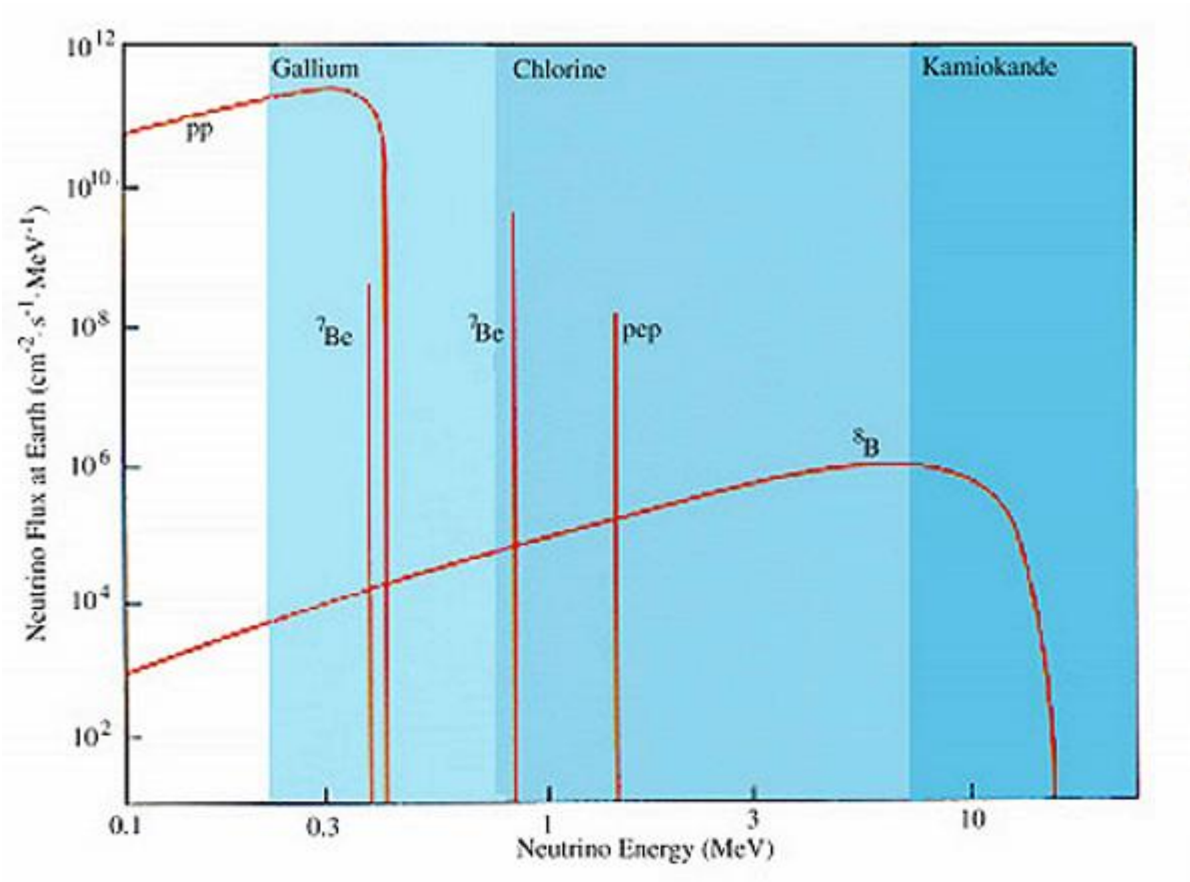
In this experiment , the neutrinos are detected via the forward scattering with electron i.e.

$$\nu_e + e^- \rightarrow \nu_e' + e^{-'}$$

It detects neutrino by the Cerenkov radiations produced by the recoiling electron. Because of the high threshold energy (approx. 7.5 MeV) for this scattering process. Kamiokande can detect only high energy neutrino ^{8}B neutrinos. The capture rate predicted by SSM is 5.05 ($1.00^{+0.20}_{-0.16}$) SNU. But experimentally measured rate is 280 ±0.38 SNU and is much below the flux predicted by SSM.

The Super Kamiokande

Super Kamiokande detects a neutrino of any flavor on the rare occasion when one of them scatters elastically off an electron in the detector's huge volume of highly purified water and imparts to it enough recoil energy to generate a wake of Cerenkov radiation. The scattering cross section for a 10-MeV electron neutrino to produce a recoil electron with an energy of at least 5 MeV is very small-only 4×10^{-44} cm^2. For the other neutrino flavors it's even smaller. Kinematics dictates that the electrons are scattered mainly within 15° of the incoming neutrino direction.



SOLAR NEUTRINO SPECTRA predicted by a standard solar model.[14] Shadings indicate lowest-energy thresholds of the various first-generation detectors. Neutrinos from the dominant proton-proton fusion reaction in the solar core can be seen only by the gallium detectors. The chlorine detector can see monoenergetic neutrino lines from electron-assisted proton fusion (pep) and from electron capture by beryllium-7 nuclei.^{7}Be also produces boron-8 in the solar core. The subsequent ^{8}B decay produces neutrinos so energetic that Kamiokande can see them. The monoenergetic line fluxes are shown in $cm^{-2}\cdot s^{-1}$. The second-generation water-Cerenkov experiments hope to have neutrino-energy detection thresholds of about 5 MeV.

Super Kamiokande's neutrino-energy detection threshold depends primarily on the intensity of low-energy background events. A 10-MeV electron generates about a thousand Cerenkov photons at visible wavelengths as it traverses the detector. These photons are monitored by 11000 photomultiplier tubes uniformly arrayed on the detector's inner walls. With this imposing coverage, Super Kamiokande has an effective neutrino energy threshold of 5 MeV.

Because of their ability to measure electron directions by means of the Cerenkov light pattern, water-Cerenkov detectors, unlike radiochemical detectors, have a handle on the incident direction of the scattering neutrino. Thus the prototype Kamiokande detector, in 1989, was the first to show directly that the observed neutrinos do indeed come from the direction of the Sun.

Early last year, after 9 years of fruitful service Kamiokande's solar-neutrino mission came to an end. Sitting a kilometer underground in the Kamioka zinc mine, about 200 km west of Tokyo, Kamiokande had a fiducial volume of only 700 tons of water, monitored by about a thousand 50-cm photomultiplier tubes. Because of a significant contamination of radon dissolved in the water, Kamiokande could not reliably detect electrons with a recoil energy of less than 7 MeV.

Kamiokande's total recorded flux of ^{8}B neutrinos was just about half of what the standard model predicted, as calculated by John Bahcall and Marc Pinsonneault.[14] The shape of the recoil electron energy spectrum was consistent with the standard model predictions, but the statistical uncertainties were large. Within the statistical errors, Kamiokande found no interesting time variation of the neutrino flux. To make further progress toward solving the solar neutrino problems with a water-Cerenkov detector, one needs a larger target volume and a lower energy threshold.

To that end the ambitious Super Kamiokande proposal was put forward. It was approved in 1991 and construction began in December of that year. In addition to advancing the study of solar neutrinos, the new facility will also be exploited to expand a number of other investigations to which its predecessor has made important contributions: the apparent deficit of muon neutrinos in cosmic ray showers (PHYSICS TODAY, October 1994, page 22), the search for proton decay and, with luck, the observation of supernova neutri

The collaboration currently consists of about 100 scientists from 11 Japanese and 12 US institutions. The US contingent has produced an anticoincidence counting system for the outer detector.

Super Kamiokande sits in a large cylindrical excavation in the Kamioka zinc mine. The bottom and side walls of the cavity are lined with stainless steel plates to form a 50000-m^3 water tank. The eleven thousand 50-cm photomultiplier tubes have been installed on an enclosing frame 3 m inside the tank walls, so that the inner volume monitored by the tubes is 32000 m^3. The 3-m-thick water layer between the frame and the tank walls is watched over by 1800 smaller photomultipliers, whose function is to veto cosmic ray muons and radioactivity from the surroundings.

With all the water and all the photomultiplier tubes in place, Super Kamiokande began looking for neutrinos and proton decays on 1 April. It is expected to record about 10000 solar neutrino collisions a year that's 80 times the rate of its predecessor.

The photomultiplier array provides a photosensitive coverage of 40%, twice as good as Kamiokande's coverage. The greater coverage lowers the neutrino detection threshold by 2 MeV and improves the electron energy resolution by 40%. This better resolution helps discriminate against a significant background of electrons from bismuth-214 beta decay, which has an endpoint energy of 3.3 MeV.

SUDBURY NEUTRINO OBSERVATORY (SNO)

SNO is a new solar neutrino detector that was constructed in Canada to search for definitive evidence of this postulated new neutrino physics. BNL joined this collaboration in early 1996. The SNO neutrino detector began taking data in October 1990.

SNO was designed to detect neutrino interactions as they occur in real time with energies > 5 MeV. It is situated in a specially constructed underground clean area, at the 6800-foot level of the Creighton mine, which is operated by INCO, the International Nickel Co., near Sudbury, Ontario. The detector contains 1000 tons of ultra-pure heavy water, D_2O, in a 12-meter wide transparent acrylic plastic vessel, surrounded by 7000 tons of ultra-pure light water, H_2O, which acts as shielding. The D_2O, with a value of about $300 million, is being lent by the Canadian Government. In the H_2O, 9600 photomultiplier tubes (PMT's) surround and view the acrylic vessel, detecting the Cerenkov light produced in the D_2O by neutrino interactions and thus measuring the neutrino energy-spectra and fluxes.

Although SNO is not a radiochemical neutrino detector, chemistry still plays a crucially important role in the SNO project. For the detector to function properly, the amounts of radioactive impurities, such as those in the U-238 and Th-232 decay chains, and Rn-222 from the mine air, must be reduced to extraordinarily low levels (e.g., 10^{-15} gram Th per gram D_2O). Other chemical contaminants must also be removed completely, since both the D_2O and H_2O must be optically transparent to allow the Cerenkov light to reach the PMT's .

The deuteron in the D_2O in SNO makes it unique among neutrino detectors, since it can observe all three neutrino flavors. The electron neutrino is the only flavor that can convert the D into 2 protons + a negative electron. This electron provides the signal for the so-called "charged current" (CC) neutrino reaction. However, all three neutrino flavors are equally effective in breaking apart the D into its constituents, a proton + a neutron. This neutron provides the signal for the "neutral current" (NC) interaction. If SNO were to measure the NC rate to be greater than the CC rate, this would be definitive proof, a "smoking gun", for the existence of neutrino oscillations. The cause of the solar neutrino problem would be the transformation of some of the solar electron neutrinos into the other flavors. The physics community is excited by this prospect for new physics. A spin-off of such a result is that massive neutrinos could account for the "missing mass" that is required for a closed universe.

1.3. Atmospheric Neutrino Experiments

The neutrino oscillation hypothesis gained support from the Japanese experiment super-Kamiokande which in 1998 showed that there was deficit of muon neutrinos

reaching earth which are produced when cosmic rays strike the upper atmosphere, the so called atmospheric neutrinos. The Super-Kamiokande experiment consists of thousands of tones of pure water in a tank deep underground, and was originally built to search for proton decay. However, its designers realized that the experiment might also be able to detect highly energetic neutrinos from the Sun that interact with electrons via scattering reactions. These electrons can travel faster than the local speed of light in the water, causing them to emit the optical equivalent of a sonic boom - a glow of blue light called Cerenkov radiation that can be detected by ultra-sensitive photomultiplier tubes around the tank. Super-Kamiokande also measured the number of electron and muon neutrinos that arrive at the Earth’s surface as a result of cosmic ray interactions in the upper atmosphere, which are referred to as “atmospheric neutrinos”. While the number and angular distribution of electron neutrinos is as expected, Super-Kamiokande showed that the number of muon neutrinos is significantly smaller than expected and that the flux of muon neutrinos exhibits a strong dependence on the zenith angle. These observations gave compelling evidence that muon neutrinos undergo flavour oscillations and this in turn implies that at least one neutrino flavour has a non-zero mass. The standard interpretation, well supported by current data, is that muon neutrinos are oscillating into tau neutrinos. Current atmospheric neutrino oscillation data are well described by simple two-state mixing.

$$\begin{pmatrix} \nu_\mu \\ \nu_\zeta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

and the two-state probability oscillation formula

$$P(\nu_\mu \rightarrow \nu_\zeta) = \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L/E)$$

where

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

and m_i are the physical neutrino mass eigenvalues associated with the mass eigenstates ν_i. Δm^2_{32} is in units of eV^2, the baseline L is in km and the beam energy E is in GeV. The atmospheric data results support maximal mixing, with best-fit two-neutrino oscillation parameters of

$$\sin^2 2\theta_{23} = 1,\ \Delta m^2_{32} = 2.6 \times 10^{-3} eV^2$$

The 90% C.L. range for Δm^2_{32} at $\sin^2 2\theta_{23} = 1$ is between 2.0 and $3.2 \times 10^{-3} eV^2$.

The approximately maximal mixing angle $\theta_{23} = 45^\circ$ means that we identify the heavy atmospheric neutrino eigenstate of mass m_3 as being approximately

$$\nu_3 \approx \nu_\mu + \nu_\zeta / \sqrt{2}$$

and in addition there is a lighter orthogonal combination of mass m_2, where

$$m^2_3 - m^2_2 = 2.6 \times 10^{-3}\ eV^2.$$

If $m_3 \gg m_2$ then this implies $m_3 \approx 0.05$ eV.

Since most neutrinos pass unhindered through the earth, this experiment was able to detect muon neutrinos coming from above and below, and found that while the correct number of muon neutrinos came from above, only about a half of the expected number came from below. The results were interpreted as half the muon neutrinos from below oscillating into tau neutrinos over an oscillating length L of the diameter of earth, with muon neutrinos from above having a negligible oscillating length, and so not having time to oscillate, yielding expected number of muon neutrinos from above.

1.4. REACTOR NEUTRINO EXPERIMENTS

Reactor experiments detect the anti-electron neutrinos which are produced copiously in the cores of nuclear reactors, and interpret any deficit in the expected number of such particles in terms of neutrino oscillations. The solar neutrino background is low because the Sun produces electron neutrinos, with negligible numbers of anti-electron neutrinos. The CHOOZ reactor experiment in France failed to see any signal of anti-neutrino oscillations over the Super-Kamiokande mass range. CHOOZ data from

$\bar{\upsilon}_e \rightarrow \bar{\upsilon}_e$ disappearance not being observed provides a significant constraint on θ_{13} over the Super-Kamiokande (SK) prefered range of Δm^2_{32} [9]:

$$\sin 2\theta_{13} < 0.04 .$$

The CHOOZ experiment therefore limits $\sin\theta_{13} \leq 0.2$ or $\theta_{13} \leq 12^\circ$ over the favoured atmospheric range at 90% C.L. The experiment is currently being upgraded to Double CHOOZ, to increase the sensitivity on the angle θ_{13}. The phase δ also appears in the third matrix, and physically represents CP violation. Since, the angle θ_{13} has not yet been measured, it might seem somewhat premature to discuss the phases associated with this angle. Nevertheless, there is, in fact, a huge experimental effort under way to both measure the angle θ_{13} and the CP phase δ. However it should be emphasized that the CP-violation in the lepton sector is one of the most challenging frontiers in the future studies of neutrino mixing. Nevertheless the experimental searches for CP-violation in neutrino oscillations can help answer the fundamental question about the status of CP-symmetry in the lepton sector at low energy. The observation of leptonic CP-violation at low energies will have far reaching consequences, and can shed light, in particular, on the possible origin of the baryon asymmetry of Universe.

1.5. EXPERIMENTS IN FUTURE.

Further experimental progress from SNO and KamLAND will consist of pinning down LMA MSW parameters to high accuracy. Neutrino physics has, now entered the precision era. Future neutrino oscillation experiments, will give accurate Information about the mass squared splittings $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, mixing angles, and CP violating phase. In the near future much better solar neutrino measurements will be available as KamLAND, SNO and Borexino furnish us with new and better data. The K2K long baseline (LBL) experiment from KEK to Super-Kamiokande has recently reported results in its phases I and II, which cover the atmospheric region and support the Super-Kamiokande results. In the longer term LBL experiments such as MINOS and eventually the CERN to Gran Sasso experiments will given more accurate determinations of the atmospheric parameters, eventually to 10%. J-PARC will be an “off-axis superbeam” over a LBL of 295 km to Super-Kamiokande due to start in 2008. Its first goal is to measure θ_{13} or set a limit on it of about 0.05 (as compared to the CHOOZ limit on θ_{13} of about 0.2). Interestingly, MINOS over a LBL of 735 km is more sensitive than J-PARC to

matter effects, so there should be some interesting complementarity between these two experiments, which could for example allow the sign of Δm^2_{32} to be determined. The ultimate goal of oscillation experiments however is to measure the CP violating phase δ. An upgraded J-PARC with a 4W proton driver and a 1 megaton Hyper-Kamiokande detector, or some sort of Neutrino Factory based on muon storage rings would seem to be required for this purpose [10]. Oscillation experiments are not capable of telling us anything about the absolute scale of neutrino masses. The Tritium beta decay experiment KATRIN will tell us about the absolute scale of neutrino mass down to about 0.35 eV. The neutrinoless double beta decay experiment GENIUS will probe the Majorana nature of the electron neutrino down to about 0.01 eV . Recent results from the 2dF galaxy redshift survey and WMAP, when combined with oscillation data, give the strong limit on the absolute mass of each neutrino species of about 0.23 eV [11, 12]. Turning to astrophysics, a galactic supernova could give valuable information about neutrino masses [13]. In future detection of energetic neutrinos from gamma ray bursts (GRBs), by neutrino telescopes such as ANTARES or ICECUBE could also provide important astrophysical information, and may provide another means of probing neutrino mass, and even quantum gravity.

1.6.Neutrino Interactions

Since neutrinos themselves cannot be directly detected, Super-Kamiokande detects the by-products of their interactions inside the water volume of the detector and the nearby rock outside. Two sources of neutrinos are available for our studies.

"Atmospheric" neutrinos are produced when cosmic ray particles from outer space collide with the Earth's atmosphere, producing a spray of secondary particles including electron- and muon-neutrinos. Neutrinos are produced in the atmosphere above Super-Kamiokande, and everyplace else on Earth. Hence neutrinos produced on the opposite side of the Earth actually pass all the way through the Earth, and arrive at the detector from below.

In addition to neutrinos produced in the Earth's atmosphere, the Sun is also a source of neutrinos. These are produced in the complex chain of reactions which generate the Sun's power. These "solar" neutrinos are all of the electron type, and are considerably

lower in energy than atmospheric ones. As a result the solar neutrino analysis is inherently more difficult since radioactive decays of materials in and around the detector create charged particles of comparable energy.

The strange disappearance of both atmospheric muon neutrinos and solar electron neutrinos can be understood as a process of "neutrino oscillation". What that means is that, given the proper conditions, a neutrino of one type can change into one of a different type; if all three neutrinos have a mass of zero, or even the same mass of any value, this would not be allowed.

If neutrinos have mass and therefore are able to change their stripes, both the atmospheric and solar neutrino anomalies could be solved. This is because muon neutrinos from the atmosphere which oscillate into tau neutrinos would be experimentally undetectable (in a practical sense). Similarly, if electron neutrinos from the Sun change into muon or tau neutrinos, they too will interact at a significantly lower rate.

1.7. Neutrino Oscillation

The term neutrino "oscillation" was coined because the transition between neutrino types is not one-way. In other words, a muon neutrino which (say) transforms into the tau type will actually transform back and forth as it sails along. This process is a probabilistic consequence of quantum mechanics. Given a neutrino produced as a certain type, after travelling a certain distance, the neutrino will become a mixture of two (or three) types. A rigorous mathematical explanation of neutrino oscillation is beyond the scope of this introduction, but the outlines can be sketched out for the simplified case where there are only two neutrinos involved in the process. It is not an easy phenomenon to explain without resorting to math, but those willing to read on may find some of their questions answered. For the truly curious, a mathematical derivation using quantum mechanics is also available.

It has long been known that particles of matter behave, in some circumstances, akin to waves instead (the effect has been observed for electrons and many other familiar particles. When particles behave like waves, they exhibit a sort of frequency which is proportional to their energy . Normally, this behavior is unimportant, since no physically observable quantity depends on whether the particle at a peak or a trough along its "matter wave".

1.8. Mixing

That is the unstated premise of neutrino oscillation; an electron neutrino, when produced must be in a quantum mechanical state which has, in effect two different masses. A muon neutrino is a similar, complementary mixture of the two masses. Conversely, a neutrino with exactly one, definite mass must be a mixture of electron and muon neutrinos. So when an electron neutrino (and its combined matter wave) is produced and starts to propagate, the two different mass values interfere with each other. Depending on the difference in frequency between the two waves, the initial electron neutrino combined wave will sometimes be dominated by one or the other waves subcomponents which has a specific mass and frequency. But if a neutrino with a definite mass is a mixture of both electron and muon neutrinos (this pre-condition for oscillation is termed "mixing"), what started as a pure electron neutrino with a mixture of masses has become a neutrino with a pure mass and a mixture of electron neutrino and muon neutrino properties. In fact the combined electron neutrino matter wave, as the two matter wave components with different masses irregularly add and cancel with each other, may even at times very closely resemble the combined *muon neutrino* matter wave. If the neutrino interacts a point where it is not in a definite state of being either an electron neutrino or a muon neutrino, which one it behaves like at that moment is anybody's guess.

The above is an attempt to sketch out the plausibility of the idea of neutrino oscillations and the implication of unequal (and hence non-zero) neutrino mass if the phenomenon is observed. It may reassure the skeptical reader to know that an essentially identical interference/mixing/oscillation scenario has in fact been experimentally observed for 20 years between two other subatomic particles called kaons. There is no question that *if* neutrino have different (non-zero) masses, and if they mix so that each neutrino represents a mixture of two or more different masses, neutrino oscillations will occur. Similarly, there is no known or imagined mechanism by which massless neutrinos would oscillate.

1.9. Mixing probability.

The masslessness of neutrino was proposed by Pontecarvo and others many years ago. Neutrinos are produced and annihilated as flavour eigenstates and they propagate through space as superposition of mass eigenstates ν_e , ν_μ, ν_τ are flavour eigenstates which can be expressed as combination of mass eigen states ν_1, ν_2, ν_3 Now for mathematical treatment we will consider the case for two neutrino flavours say ν_e and ν_μ and they will be the combination of two eigen states ν_1, ν_2 Using unitary transformation of matrices involving arbitrary mixing angle θ

$$\begin{pmatrix} \nu e \\ \nu \mu \end{pmatrix} = \begin{pmatrix} cos\theta & \sin\theta \\ -\sin\theta & cos\theta \end{pmatrix} \quad \begin{pmatrix} \nu 1 \\ \nu 2 \end{pmatrix}$$

On solving we get : -

$$\nu_{\mu} = \nu_1 \, cos\theta + \nu_2 \sin\theta$$

$$\nu_e = - \nu_1 \sin\theta + \nu_2 \, cos\theta$$

These two equations are showing wave functions in orthogonal states.Thus there propagation inspace is given by

$$\nu_1(t) = \nu_1 \, e^{-i\, E1t}$$

$$\nu_2\,(t) = \nu_2 \, e^{-i\, E2t}$$

Here we are using natural system of units so c=1 and h=1. The states ν_1 and ν_2 will have the fixed mummentum p, so that if the masses are m_1 and m_2 then the equations become: -

$$\nu_1\,(t) = \nu_2\,(0)e^{-i\,\omega 1t}$$

$$\nu_2\,(t) = \nu_2\,(0)e^{-i\,\omega 2t}$$

Now let us consider two states at time t=0 and at time t=t then these can be written as

$$|\,i> = |\,\nu_e(0)>$$

and

$$|f> = |\,\nu_e(t)>$$

now

$$amp(\nu_e \to \nu_e) = <i\,|f> = <\nu_e(0)\,|\,\nu_e(t)>$$

$$amp(\nu_e \to \nu_\mu) = <i\,|F> = <\nu_e(0)\,|\,\nu_\mu(t)$$

Also, $amp(\nu_e \to \nu_e) = cos^2\theta\ .exp(-i\,\omega_1 t) + sin^2\theta.\,(-i\,\omega_2 t)$

Transition probability:

$$(\nu_e \to \nu_e) = |amp|^2 = Re^2 + Im^2$$

$$Re = cos^2\theta\ \cos\omega_1 t + sin^2\theta\ \cos\omega_2 t$$

$$Im = cos^2\theta\ \sin\omega_1 t + sin^2\theta\ \sin\omega_2 t$$

$$P(\nu_e \rightarrow \nu_e) = = cos^4\theta + sin^4\theta + 2sin^2\theta cos^2\theta(\cos\omega_1 t \cos\omega_2 t + \sin\omega_1 t \sin\omega_2 t)$$

$$P(\nu_e \rightarrow \nu_e) = = cos^4\theta + sin^4\theta + 2sin^2\theta cos^2\theta \cos(\omega_2 - \omega_1)t$$

Now ,

$$cos^2\theta + sin^2\theta = 1$$

$$\text{So ,} \quad cos^4\theta + sin^4\theta + 2sin^2\theta cos^2\theta = 1$$

$$P = 1 - 2sin^2\theta cos^2\theta + 2sin^2\theta cos^2\theta \cos\Delta\omega$$

$$P = 1 - 4sin^2\theta cos^2\theta \sin^2(\Delta\omega t/2)$$

$$P = 1 - sin^2 2\theta \sin^2(\Delta\omega t/2)$$

This is the probability transition from v_e to v_e.

Also t= L/c ,where L is mixing lenghth.

So we get ,

$$P = 1 - sin^2 2\theta \sin^2(\Delta\omega L/2c)$$

1.10 constraints on the Neutrino Parameters from the "Rise-Up" in the Boron Neutrino Spectrum at Low Energies.

Neutrino Physics is passing through a phase of spectacular development. Vast amount of solar and atmospheric neutrino data has been accumulated and the neutrino deficits have been established to be the consequence of non-standard neutrino physics. The most recent steps in this direction are the pioneering results from SNO and KamLAND experiments. The SNO experiment provided a model independent proof of solar neutrino oscillations and the terrestrial disappearance of reactor $\overline{\nu_e}$ in the KamLAND experiment has provided a further confirmation of the neutrino oscillation solution of the solar neutrino problem (SNP). This gives us confidence in the oscillation solution of the atmospheric neutrino anomaly.

The neutral current measurements at SNO [14] have, conclusively, established the oscillations of solar neutrinos. After the evidence of terrestrial antineutrino disappearance in a beam of electron antineutrinos reported by KamLAND [15], all other [16] explanations of the solar neutrino deficit can, at best, be just subdominant effects. After these pioneering experiments, there is no scope for doubting the physical reality of neutrino mass and the consequent oscillations. KamLAND is the first experiment to explore the neutrino parameter space relevant to SNP with a beam of terrestrial neutrinos and has, convincingly, demonstrated the existence of neutrino oscillations confined to large mixing angle LMA region.The total event rate as well as the spectrum distortion at KamLAND are in good agreement with the LMA expectations. Recently, updated analyses of all the available solar and reactor neutrino data including KamLAND and SNO salt phase data have been presented [17]. However, even after the confirmation of the LMA MSW mechanism as a dominant solution of SNP, the oscillation parameters are not precisely known. A precise determination of these parameters will be of great importance for theory as well as phenomenology of neutrino oscillations in particular and particle physics in general.

The solar neutrino experiments have, already, entered a phase of precision measurements for oscillation parameters. On the other hand, the LMA solution is facing a deeper scrutiny. In fact, the completeness of the LMA solution is being questioned [18] and the scope for some possible subdominant transitions is being explored [19, 20] vigorously. Does the LMA solution satisfactorily explain all the solar neutrino data? Are there any observations indicating new physics beyond LMA? These are some of the

relevant questions being posed. It is also the high time to put the LMA predictions to closer experimental scrutiny. There are, at least, two generic predictions of LMA [19] which point towards life beyond LMA. One of these is the prediction of a high argon production rate, $Q_{AR} \approx$ 3SNU, for the Homestake experiment which is about 2σ above the observed rate. Another generic prediction of the LMA scenario is the 'spectral upturn' at low energies. Within the LMA parameter space, the survival probability should increase with decrease in energy and for the best fit point, the upturn could be as large as 10-15% between 8MeV and 5MeV [21]. However, neither the SuperKamiokande (SK) nor SNO have reported any statistically significant 'rise-up' in the observed neutrino survival probability. Both these predictions of LMA can only be tested in the forthcoming phase of high precision measurements in the solar neutrino experiments and are crucial for confirmation of the LMA solution.

The distortions in the neutrino spectrum are an important factor in resolving the solar neutrino problem. These distortions arise due to the energy dependence of the survival probability as a result of which neutrinos with different energies survive in different propor-tions leading to distortions in the observed spectrum. Experimentally, the boron neutrinos are the most accessible source for the study of the distortions in the observed spectrum since the SK and SNO detect the boron neutrinos in the small energy bins over a wide energy range. Since, the LMA has emerged as a solution of the SNP, the spectrum distortions within the LMA scenario are of paramount importance for the final confirmation of the LMA as a solution of the SNP and, also, for possible physics beyond LMA.

1.11 Constraints on the Weakly Mixed Sterile Neutrinos in the Light Of SNO salt Phase and 766.3Ty KamLAND Data.

The SNO [22, 23] and KamLAND [24] experiments have played a crucial role in resolving the longstanding solar neutrino problem in terms of large mixing angle (LMA) MSW oscillations and are expected to play an important role in the refinement of the LMA solution which is undergoing a deeper scrutiny. Does the LMA solution explain all the solar neutrino data satisfactorily? There are, at least, two generic predictions of LMA indicating new physics beyond LMA. One of these is the prediction of the high argon production rate for Homestake experiment which is about 2σ above the observed rate. Another generic prediction of the LMA scenario is the ‘spectral upturn’ at low energies. Within the LMA parameter space, the survival probability should increase with decrease in energy and for the best fit parameters, the upturn could be as large as 10-15% between 8 MeV and 5 MeV [25]. In fact, the spectral upturn at low energies is expected to increase further with the KamLAND 766.3 Ty spectral data [26] favoring a larger value of Δm^2 [27]. However, neither SuperKamiokande nor SNO has reported any statistically significant ‘rise-up’ in the observed neutrino survival probability. Both these predictions of the LMA solution can, only, be tested in the forthcoming phase of high precision measurements [28] in the solar neutrino experiments and are crucial for the final confirmation of the LMA solution.

Another unresolved issue is whether the solar neutrinos oscillate into the sterile component. The main motivation for postulating the existence of the sterile neutrino species comes from the LSND experiment which reported a significant $\overline{\nu_{\mu}} \rightarrow \overline{\nu_e}$

oscillation probability [29] which requires a new mass scale. Since, the Z-decay width constrains the number of weakly interacting light neutrino species to be very close to three [30], one is forced to postulate a sterile neutrino. While the purely sterile oscillation solution is excluded at 7.6σ [31], the solar electron neutrinos could still oscillate into both active and sterile neutrinos, a scenario which is, largely, unconstrained at present. In fact, a combined analysis [32] of solar and atmospheric neutrino data has shown that the active-sterile admixture can take any value between zero and one. While the SNO charged current data excluded the maximal mixing to

sterile neutrinos at 5.4σ [23], arbitrary active-sterile admixtures were not considered. Consequently, a significant sterile fraction in the solar neutrino flux reaching the earth is, still, possible. The discovery of the sterile neutrinos would be of great importance for particle physics, even though, it is, still, not clear how these hypothetical 'exotic' degrees of freedom would fit into elementary particle theory.

The possibility of subdominant transitions into sterile neutrino states accompanying the dominant LMA flavor transitions has been examined earlier [33] and upper bounds on the sterile neutrino fraction in the non-electronic boron neutrino flux have been derived. How-ever, the subdominant transitions into sterile states have neither been confirmed nor ruled out at a statistically significant level. In the present work, the possibility of flavor transitions into sterile component in the solar boron neutrino flux has been examined in a model pre-sented by Hollanda and Smirnov [25] to lower the abnormally high argon production rate in the Homestake experiment and, also, to lower the 'spectral upturn' in the low energy boron neutrino spectrum predicted in the pure LMA scenario.

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CHAPTER-2

CONSTRAINS ON THE NEURINO PARAMETERS FROM THE “RISE-UP” IN THE BORON NEUTRINO SPECTRUM AT LOW ENERGIES

In the present work, we focus on the 'rise-up' in the neutrino spectrum at low energies and demonstrate how a precision measurement of the 'upturn' can be used to further constrain the neutrino parameter space allowed by the SNO salt phase data. In the absence of concrete experimental results on the 'rise-up', we obtain indirect bounds on the 'rise-up' in the boron neutrino spectrum by comparing the boron neutrino survival probability obtained from the experiments with the asymptotic value of the corresponding LMA survival probability.

The apparent lack of the 'rise-up' in the observed boron neutrino spectrum at low energies has been sought to be explained by introducing subdominant transitions into sterile neutrinos [1] and/or antineutrinos [2]. In the present work, it has been shown that the 'rise-up' in the boron neutrino spectrum can be reduced significantly by choosing a suitable point within the LMA parameter space itself. We examine the status of this 'rise-up' within the pure LMA scenario in the following manner. From the SNO salt phase data and the value of the neutrino mixing angle 'θ' obtained from the global analyses, indirect bounds on the 'rise-up' are obtained. The constraints on the 'rise-up' and the boron neutrino survival probability are combined to further constrain the neutrino parameter space allowed by the SNO.

The LMA survival probability [3], to a very good approximation, can be written as

$$P = \frac{1}{2} + \frac{1}{2} \cos 2\theta \cos 2\theta_{\mathbf{m}} \qquad (2.1)$$

Where the mixing angle in matter is given by

$$\cos 2\theta m = (\cos 2\theta - \beta)/\sqrt{q(\cos 2\theta\ -\ \beta)2\ +\ \sin 2\ 2\theta} \qquad (2.2)$$

and the ratio of matter to vacuum effects 'β' is given

$$\beta = 2\sqrt{2}\ G_F N_e E\ /\ \Delta m^2 \qquad (2.3)$$

E is the energy of the neutrino and Ne is the electron number density at the point of maximal boron neutrino production i.e.e at. $x = R/R_S = 0.05$ where R_S is the solar radius so that

$$G_F\ N_{\mathbf{e}} = 0.4714 \times 10^{-11} e \qquad (2.4)$$

at this point [4]. The energy dependence of the LMA survival probability P given by eqn. (2.1) is shown in Fig.1 (dashed line) along with its asymptotic value $\sin^2\theta$

(dotted line). The survival probability averaged over the production region of the boron neutrinos [9] has been plotted as a solid line. It can be easily seen that the analytical expression (2.1) is in fairly good agreement with the exact numerical result. The value of P is slightly increased by averaging over the production region. Moreover, the earth regeneration effects will, also, increase the survival probability only by a small amount. It can be seen that the percentage increase in the survival probability from the earth regeneration effects equals the day-night asymmetry. The expected day-night asymmetry at SNO is about 3% [4]. Thus, eqn. (2.1) is a fairly good approximation to survival probability.

Eq (2.1) can be written as

$$P=\sin^2\theta + R \tag{2.5}$$

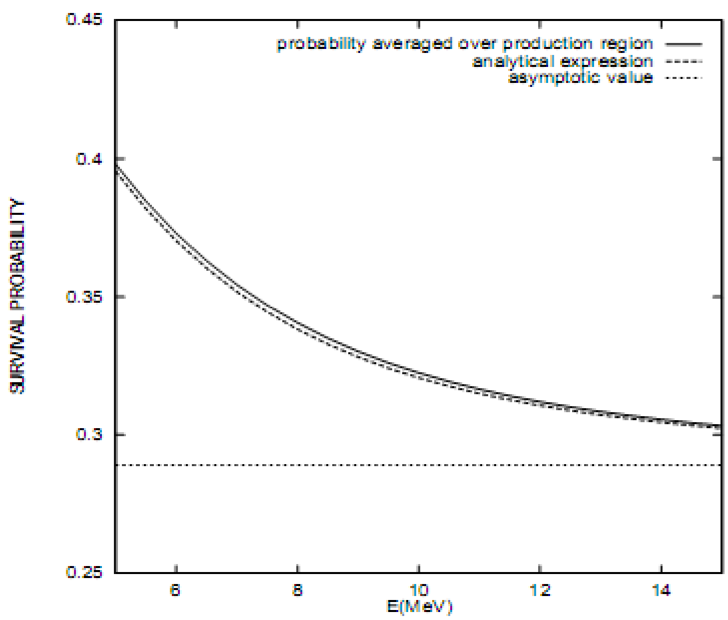

Fig1. The energy dependence of boron neutrino survival probability in the LMA scenario for $\Delta m^2 = 7.1\times10^{-5}\,eV^2$ and $\theta = 32.5^o$

where

$$R = \cos 2\theta \cos^2\theta_m \qquad (2.6)$$

is the rise-up in the survival probability. Obviously, R is always positive and increases with decrease in energy. The survival probability P is an increasing function of both Δm^2 and θ in the allowed LMA region in contrast to R which is increasing function of Δm^2 and decreasing function of θ ,within this region. The 'rise-up' R becomes zero for maximal mixing. Since, maximal mixing is rejected at 5.4 standard deviations, the 'rise-up' cannot be zero. Hence, a non-zero 'rise-up' is an inescapable consequence of the LMA scenario.

Global analysis of the SNO salt phase data along with other solar and reactor neutrino data yields [5].

$$\Delta m^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}\ \mathrm{eV}^2, \qquad (2.7)$$

$$\theta = 32.5^{+2.4}_{-2.3}\ \mathrm{deg} \qquad (2.8)$$

For these LMA parameters ,we have

$$\sin^2\theta = 0.289^{+0.038}_{-0.036} \qquad (2.9)$$

$$P = 0.362^{+0.036}_{-0.031} \qquad (2.10)$$

$$R = 0.074^{+0.044}_{-0.025} \qquad (2.11)$$

It is clear that R is about three standard deviations above zero and is large enough to be measured experimentally.

The value of the survival probability for the boron neutrinos can be calculated from the SNO CC and NC rates using the relation

$$P = \frac{\Phi_{CC}^{SNO}}{\Phi_{NC}^{SNO}} \qquad (2.12)$$

where we have assumed transitions into active flavors only. Transitions into sterile neutrinos can be important and will be studied elsewhere . Even though, neither SK nor SNO has reported any statistically significant 'rise-up', one can infer the 'rise-up' at 6.4MeV from SNO CC/NC ratio. Since, $\sin^2\theta$ is constrained by equation (2.9), we can constrain R using eqns. (2.5) and (2.9). In this manner, we can obtain an indirect upper bound on R. However, the value of θ obtained from the global analyses is not model independent as a result of which the value of R obtained in this manner will be model dependent and will be valid only within the LMA scenario.

The pure D_2O data from SNO [6] gives

$$\Phi_{CC}^{SNO} = 1.76_{-0.103}^{+0.108} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \quad (2.13)$$

$$\Phi_{CC}^{SNO} = 6.42_{-0.167}^{+0.166} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \quad (2.14)$$

where the statistical and the systematic errors have been combined in quadratures.. equation (2.12), we have

$$P = 0.274_{-0.073}^{+0.073} \quad (2.15)$$

Using the LMA value of θ and equation (5), one can obtain

$$R = -0.015_{-0.081}^{+0.082} \quad (2.16)$$

which is not, significantly, different from zero. However, one can obtain an upper bound on R from eq.(2.16) viz.

$$R \leq 0.120 \quad (2.17)$$

at 90%C.L. It may be worthwhile to mention that the NC rate given in equation (2.14) has been obtained without any assumptions regarding the energy dependence of the survival probability. If one assumes an undistorted boron neutrino spectrum and, hence, an energy independent survival probability, SNO pure D_2O data gives

$$\Phi_{CC}^{SNO} = 5.09_{-0.608}^{+0.637} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \quad (2.18)$$

Using this value instead of the value quoted in equation (2.14) would give

$$P = 0.346_{-0.046}^{+0.048} \quad (2.19)$$

And

$$R = 0.057_{-0.058}^{+0.061} \quad (2.20)$$

in agreement with the LMA values given in eqns. (2.10) and (2.11). However, the LMA survival probability being energy dependent, the use of the value quoted in equation (2.18) for deriving constraints on neutrino parameters will not be internally consistent [7].

The most recent SNO salt phase data [6]

$$\frac{\Phi_{CC}^{SNO}}{\Phi_{NC}^{SNO}} = 0.306_{-0.035}^{+0.035} \quad (2.21)$$

can also be used to obtain the new bounds on P and R viz.

$$P=0.306^{+0.035}_{-0.035} \tag{2.22}$$

$$R=0.017^{+0.052}_{-0.050} \tag{2.23}$$

This value of 'rise-up' will be used henceforth. The value of P given in equation (2.22) is smaller than the mean LMA value by an amount

$$0.057^{+0.068}_{-0.056} \tag{2.24}$$

which is one standard deviation above zero. We shall explore the allowed LMA region to reduce the difference between the LMA values of P, R and their experimental values given by eqns. (2.22) and (2.23) respectively which imply the following upper bounds on P and R:

$$P \leq 0.363 \tag{2.25}$$

$$R \leq 0.102 \tag{2.26}$$

at 90% C.L. As noted earlier the "rise up" R becomes smaller for smaller values of Δm^2 and larger values of θ. However, a larger value of θ leads to an increase in the value of P. In fact, the experimental value of P is already greater than the mean LMA value and cannot be increased further. Hence, we consider the constraints (2.25) and (2.26) on P and R simultaneously. This can be achieved by plotting the constant P and constant R curves in the allowed parameter space. The curves corresponding to 90% C.L. upper bounds on P and R have been plotted in Fig.2 within the LMA parameter space allowed by the SNO. The overlap region below P and R curves is the region of parameter space allowed by the bounds on "rise-up" and survival probability obtained above.The resulting upper bounds on Δm^2 and θ are

$$\Delta m^2 \leq 7.9 \times 10^{-5}\ eV^2 \tag{2.27}$$

$$\theta \leq 33.7^{o} \tag{2.28}$$

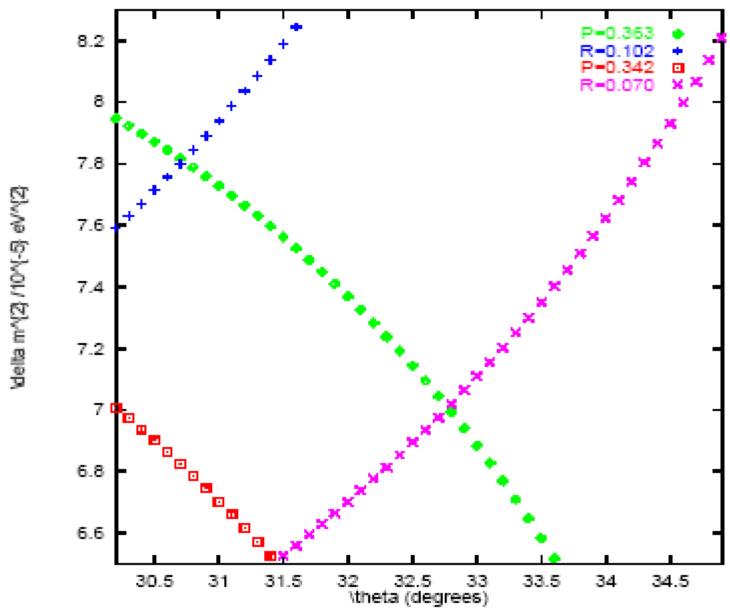

Fig. 2. The constant P and the constant R curves plotted within the neutrino parameters space allowed by SNO salt phase data.

at 90% C.L. Thus, the 'rise-up' in the boron neutrino spectrum can be used to further restrict the neutrino parameter space. In fact, the bound on the 'rise-up' derived from SNO salt-phase data selects lower values of Δm^2 consistent with the conclusions reached by Aliani et al [8] who incorporated the SNO spectrum data in the global analysis. Therefore, the 'pure LMA' scenario will get rejected at more than 90% C.L. if the future precision measurements favor $\Delta m^2 > 7.9 \times 10^{-5} eV^2$. The value of Δm^2 larger than $7.9 \times 10^{-5} eV^2$ will be clear signature of physics beyond LMA being manifest in the oscillations of solar boron neutrinos. The inclusion of the earth regeneration effect as well as the averaging over the production region will only decreases the value of Δm^2 and the upper bound mentioned above will, still, remain valid.

The curves P=0.342 and R=0.070 corresponding to 1.02σ C.L. are also shown in Fig. 2 below which there is no overlap. These two curves intersect at

$$\Delta m^2 = 6.5 \times 10^{-5} eV^2, \tag{2.29}$$

$$\theta = 31.4^o \tag{2.30}$$

For these values of Δm^2 and θ, the difference between the LMA values of P, R and their experimental values (2.22) and (2.23) is the least (about one standard deviation). This can be regarded as the best fit point in the SNO allowed parameter space. The values of Δm^2 and θ obtained from the global analyses of all the solar neutrino data [5] are very close to the values obtained here.

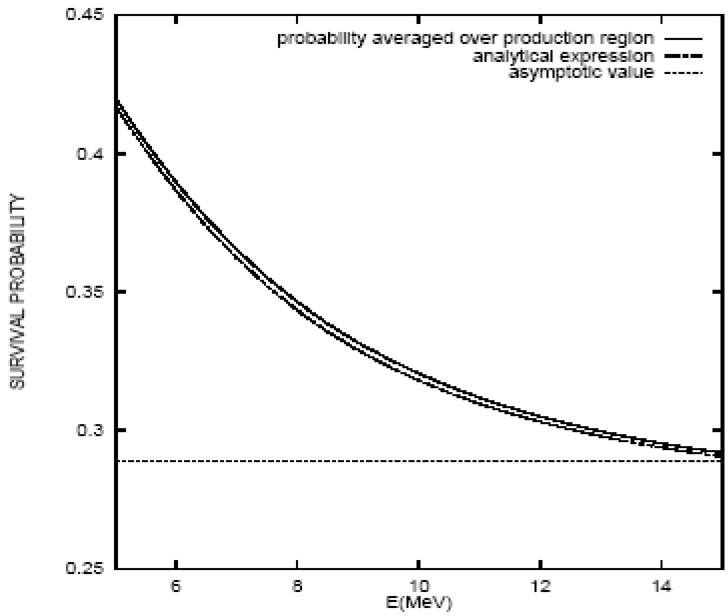

Fig.3. The same as in Fig.1 but for the values of $\Delta m^2 = 8.3\times10^{-5}$ eV^2 and $\theta = 31.3^o$

While this work was in progress, KamLAND reported 766.3 Ty spectrum data [9] which has been combined with the solar neutrino data by several authors [5,8,9]. The two main implications of the new KamLAND data are the increase in the value of Δm^2 to $8.3^{+0.40}_{-0.37}\times 10^{-5}$ eV^2 and a decrease in the best fit values of θ to $31.3^{+1.9}_{-1.3}$ deg.[9].The best fit value of Δm^2 obtained in Ref. 9 is larger than the upper bound derived here.This can be regarded as an indication of Physics beyond LMA.

The inclusion of the earth regeneration effects will increase the values of P and R by only about 3% which is too small as compared to the rise-up (which is about 28%) [see Fig. 3]. Moreover, the LMA values of P and R are, already, larger than their experimental values. The earth regeneration effect will, therefore, further increase their values enhancing the mismatch between theory and experiment.This would make the upper bound on Δm^2 even more restrictive.

For these values of Δm^2 and θ ,P and R now will become

$$P=0.376^{+0.017}_{-0.014} \qquad (2.31)$$

$$R=0.106^{+0.023}_{-0.025} \qquad (2.32)$$

in place of eqns. (3.10) and (3.11). The difference of P from its experimental value (eqn. (2.22)) is given by

$$0.076^{+0.039}_{-0.038} \qquad (2.33)$$

which is 2σ above zero. Hence, there is considerable difference between the experimental and theoretical values of P in the LMA scenario. Since, there are very stringent bounds on the solar antineutrino flux [10], the transitions into antineutrinos can not account for this difference. Hence, we attribute the whole of this difference to the transitions into sterile neutrinos and obtain[11].

$$P(\nu_e \rightarrow \nu_e) = x\sin^2\alpha / (1-x\cos^2\alpha), \qquad (2.34)$$

$$P(\nu_e \rightarrow \nu_\mu) = (1-P(\nu_e \rightarrow \nu_e)) \sin^2\alpha \qquad (2.35)$$

$$P(\nu_e \rightarrow \nu_S) = (1-P(\nu_e \rightarrow \nu_e)) \cos^2\alpha \qquad (2.36)$$

Where

$$x = \frac{\Phi^{SNO}_{CC}}{\Phi^{SNO}_{NC}} \qquad (2.37)$$

and

$$P(\nu_e \rightarrow \nu_\mu)=1-P_{LMA} \qquad (2.38)$$

Here, α is the sterile mixing angle. From these equations, we obtain

$$P(c_e \rightarrow \nu_e)=x(1-P_{LMA}) / (1-x) \qquad (2.39)$$

And

$$\sin^2\alpha = 1- \frac{P_{LMA} - x}{1-2x+xP_{LMA}} \qquad (2.40)$$

Using equation (2.21) for x and equation (2.31) for P_{LMA}, we obtain

$$\sin^2\alpha = 0.861^{+0.091}_{-0.077} \qquad (2.41)$$

and

$$P(\nu_e \rightarrow \nu_e) = 0.275^{+0.055}_{-0.049} \tag{2.42}$$

The pure sterile solution($\sin^2\alpha = 0$) is disfavored at 11.2 standard deviations.

From eq (2.39), we obtain

$$P(\nu_e \rightarrow \nu_S) = 1.101^{+0.066}_{-0.069} \tag{2.43}$$

At 3σ C.L which implies

$$P(\nu_e \rightarrow \nu_S) \leq 0.299 \tag{2.44}$$

The sterile flux is non-zero at about 1.5 standard deviations. A more elaborate analysis is needed to constrain the sterile component using the approach adopted here and will be presented elsewhere.

2.1.CONCLUSIONS

In conclusion, the 'rise-up' in the boron neutrino spectrum at low energies has been stud-ied within the framework of the LMA scenario. Indirect bounds on the rise-up have been obtained from the available solar neutrino data. These bounds have been used to demon-strate as to how a precision measurement of the rise-up can be used to further constrain the neutrino parameter space allowed by the SNO salt phase data. It is found that the pure LMA solution is sufficient to explain the SNO salt phase data for $\Delta m^2 \leq 7.9 \times 10^{-5}$ eV^2 and $\theta \leq 33.7^o$ since larger value of Δm^2 will violate the upper bound in eq.(2.26). However, the most recent global analyses [9, 5, 8] of the solar neutrino and the recent KamLAND data favor a value of Δm^2 which violates this upper bound. Consequently, pure LMA solution seems to be disfavored and other subdominant transitions seem unavoidable. The theoretical and experimental values of the boron neutrino survival probability in the pure LMA scenario for the most recent LMA parameters differ by two standard deviations. This discrepancy is too large to be explained by the subdominant SFP transitions into an-tineutrinos. In the present work, this discrepancy has been attributed to the subdominant transitions into the sterile neutrinos. It is concluded that the sterile neutrino flux in this scenario could be as large as 0.299 times the boron neutrino flux at 3σ.[12].

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CHAPTER-3

CONSTRAINTS ON WEAKLY MIXED STERILE NEUTRINOS IN THE LIGHT OF SNO SALT PHASE AND 766.3 TY KAMLAND DATA

3.1 Weakly Mixed Sterile Neutrinos

$$\nu_0 = (\cos\alpha)\,\nu_s + \sin\alpha\{(\cos\theta)\,\nu_e - (\sin\theta)\,\nu_\mu\},$$
$$\nu_1 = (\cos\alpha)\{(\cos\theta)\,\nu_e - (\sin\theta)\,\nu_\mu\}, - (\sin\alpha)\,\nu_s \qquad [3.1]$$
$$\nu_2 = (\sin\theta)\,\nu_e + (\cos\theta)\,\nu_\mu$$

with masses m_0, m_1 and m_2, respectively. It is assumed that $\sin^2\alpha \ll 1$ (weak mixing) so that ν_s is mainly present in the mass eigenstate ν_0 only. Following Hollanda and Smirnov [1], we assume the mass hierarchy $m_1 < m_0 < m_2$, and define the following mass squared differences:

$$\Delta m_{01}^2 = \Delta m_0^2 - \Delta m_1^2$$
$$\Delta m_{01}^2 = \Delta m_2^2 - \Delta m_1^2 \qquad [3.2]$$

The energy eigenlevels for the above neutrino system (ν_0 , ν_1 and ν_2) are denoted by λ_0, λ_1 and λ_2, respectively. For the mass hierarchy assumed above, the level λ_0 crosses the level λ_1.

only and λ_2 is, approximately, the same as it would be in the pure LMA two z scenario in the absence of any sterile mixing. Neglecting the small admixture of ν_e in ν_0, one obtains

$$P_{ee} = P_{LMA} - P_{es}\cos^2\theta \qquad [3.3]$$

$$P_{e\mu} = 1 - P_{LMA} - P_{es}\sin^2\theta \qquad [3.4]$$

$$P_{es} = \cos^2\theta_m(\sin^2\alpha_m + P_c\cos 2\alpha_m), \qquad [3.5]$$

Where P_{LMA} is given by

$$P_{LMA} = \frac{1}{2} + \frac{1}{2}\cos 2\theta\cos\theta_m \qquad [3.6]$$

is the survival probability for electron neutrinos in the pure LMA scenario. P_C is the crossing probability at the point where λ_0 and λ_1 cross while θ_m and α_m are the mixing angles in the matter. The symbols P_{ee} , $P_{e\mu}$ and P_{es} have their usual meaning. Hollanda and Smirnov [1] have shown that the introduction of sterile admixture leads to a decrease in the 'rise-up' in the boron neutrino spectrum at lower energies and, also, reduces the argon production rate at Homestake to a phenomenological acceptable level for

$$\Delta m_{01}^2 \sim (2\text{-}20) \times 10^{-5}\ \text{eV}^2,$$

$$\text{Sin}^2 2\alpha \sim (10^{-5}\text{-}10^{-3}). \qquad [3.7]$$

Apart from some rather 'exotic' scenarios proposed in literature [10], it happens to be the simplest and the most plausible scenario to overcome the generic problems of the pure LMA solution mentioned earlier. Therefore, it is important to constrain the sterile component in this scenario (referred to as the (LMA+sterile) scenario, henceforth) in the light of the SNO solar neutrino data.

In this (LMA+sterile) scenario

$$P_{ee} = \frac{\Phi_{CC}^{SNO}}{\phi_B}, \qquad [3.8]$$

$$P_{e\mu} = \frac{\Phi_{NC}^{SNO} - \Phi_{CC}^{SNO}}{\phi_B} \qquad [3.9]$$

$$P_{es} = \frac{\Phi_{NC}^{SNO}}{\phi_B}, \qquad [3.10]$$

where ϕ_{CC} and ϕ_{NC} are the fluxes measured at SNO through CC and NC reactions, respectively, and ϕ_B is the total boron neutrino flux.

From eqs.(3.8-3.10) ,one obtains

$$P_{e\mu} = \frac{1-x}{x} P_e \qquad [3.11]$$

and

$$P_{es} = 1 - \frac{P_{ee}}{x} \qquad [3.12]$$

where

$$x = \frac{\Phi_{CC}^{SNO}}{\Phi_{NC}^{SNO}} \qquad [3.13]$$

The ratio of nonelectronic active neutrino flux to total nonelectronic (active+sterile) neutrino flux, denoted by $\sin^2\varphi$, is given by

$$\sin^2\varphi = \frac{\Phi_{NC}^{SNO} - \Phi_{CC}^{SNO}}{\Phi_B - \Phi_{NC}^{SNO}} \qquad [3.14]$$

In the LMA scenario

$$P_{LMA} = (\nu_e \rightarrow \nu_e) = P_{LMA} = x \qquad [3.15]$$

where x is given by equation (3.13). However, in the (LMA +sterile) scenario, are not equal and one has to use the relation (3.8)

$$x = \frac{\Phi_{CC}^{SNO}}{\Phi_B}$$

instead, where ϕ_B is, now, an independent quantity which can not be determined from the SNO CC and NC fluxes. One can use the boron neutrino flux given by the standard solar model (SSM) for ϕ_B to calculate $\sin^2\varphi$ and P_{ee}. However, because of large errors in the SSM boron neutrino flux (ϕ_{SSM}), only a lower bound on $\sin^2\varphi$ can be obtained while the upper bound becomes larger than unity [9].

Without assuming P_{ee} , one cannot calculate $\sin^2\varphi$ and $\phi_{\mathbf{B}}$, uniquely and only a family of solutions corresponding to different values of $P_{ee}$is obtained. Equations (3.8) and (3.14) can be rewritten as a set of coupled equations as follows

$$\sin^2\varphi = \frac{1-x}{x}\frac{P_{ee}}{1-P_{ee}} \qquad (3.16)$$

$$\phi_B = \frac{\Phi_{CC}^{SNO}}{P_{ee}} \qquad (3.17)$$

This degeneracy is well known as the ($f_{\mathbf{B}}$ –$\sin^2\varphi$) degeneracy in the literature [9]. The value of $\phi_{\mathbf{B}}$ is, usually, given in the units of the central value of ϕ_{SSM} , so that $f_B = \phi_B/\varphi_{SSM}$).

To gain further insight into this degeneracy, we rewrite equations (3.11,3.12) as follows

$$(1-x)\, P_{ee} - x\, P_{e\mu} = 0 \qquad (3.18)$$

$$P_{ee} + x\, P_{es} = x \qquad (3.19)$$

Since, we have only two equations relating three unknowns viz. P_{ee} , $P_{e\mu}$ and P_{es}, a unique solution is not possible and one obtains a family of solutions, instead, corresponding to different values of P_{ee}. Balentekin et al. [10] identify P_{ee} with P_{LMA}

(electron neutrino survival probability in the pure LMA scenario in the absence of any sterile transitions) and use equations (3.8), (3.14) and (3.15) to constrain the sterile component. However, equation (3.15) cannot be used to derive meaningful constraints on the sterile component since one obtains $\sin^2\varphi = 1$ on substitution of equation (3.15) in equation (3.16). To overcome this problem, we use equation (3.3) alongwith equations (3.18,3.19) to constrain the sterile component. We collect all these equations below:

$$P_{ee} + P_{es}\cos^2\theta = P_{LMA} \,,$$
$$(1-x)\, P_{ee} - x\, P_{e\mu} = 0 \qquad (3.20)$$
$$P_{ee} + xP_{es} = x$$

This set of coupled equations has the following simultaneous solution

$$P_{ee} = x\frac{\cos^2\theta - P_{LMA}}{\cos^2\theta - x} \qquad (3.21)$$

$$P_{e\mu} = (1-x)\, \frac{\cos^2\theta - P_{LMA}}{\cos^2\theta - x} \qquad (3.22)$$

$$P_{es} = \frac{P_{LMA} - x}{\cos^2\theta - x} \qquad (3.23)$$

3.3.RESULTS AND DISCUSSION

In order to examine the possibility of transitions into sterile neutrinos, we plot the 1σ allowed and lower values of $P_{ee} = \frac{\Phi_{CC}^{SNO}}{\phi_B}$ [eq.(3.8)] allowed by the salt phase SNO data [2] and BP04 [15] in Figure 1 which, also, depicts P_{ee} as a function of P_{es} as given by equation (3.12). It is clear from Figure 1 that significant transitions into sterile neutrinos are allowed by the SNO salt phase data and, in fact, the 1σ upper bound on P_{es} could be as large as 0.4. More precise bounds on the sterile fraction in the boron neutrino flux can, only, be obtained with more precise measurements of CC and NC rates at SNO in the future. It may be pertinent to mention here that the boron neutrino flux estimates in the SSM have, rather, large uncertainties. Consequently, considerable improvements in the boron neutrino flux estimates in the SSM are required for obtaining meaningful constraints on the possible sterile neutrino fraction in the boron neutrino flux.

One can obtain the electron neutrino survival probability P_{ee}, the transition probability into muon neutrinos $P_{e\mu}$ and the transition probability into the sterile neutrinos P_{es} from equations (3.21-3.23) by substituting the flux-averaged value of P_{LMA} (calculated for the values of Δm^2 and θ and 1σ errors therein taken from [13]) and the value of x reported by SNO [16]. It is important to realize here that the SNO CC flux is the actual electron neutrino flux ϕ_{ν_e} if the boron energy spectrum is assumed to be undistorted. Since, the SuperKamiokande[17] (with a better precision) has not reported any, statistically significant, spectral distortions in the boron neutrino spectrum, we assume an undistorted boron neutrino spectrum and identify $P_{LM\ A}$ with x at the high energy end. However, since the LMA scenario predicts a significant spectral upturn at lower energies [6], $P_{LM\ A}$ is expected to be, significantly different from x at lower energies. For the flux averaged value of P_{LMA} , $P_{ee} = 0.239^{+0.063}_{-0.055}$, $P_{e\mu}=0.543^{+0.042}_{-0.048}$ and $P_{es}=0.218^{+0.103}_{-0.105}$ which is non zero at about 2.1σ. The probabilities P_{ee}, $P_{e\mu}$ and P_{es} have been plotted in Figure 2 as functions of x where the 1σ upper and lower bounds have, also, been shown. It is clear from Figure 2 that the 1σ values of $P_{\mathbf{ee}}$ and $P_{\mathbf{es}}$ are of comparable magnitude. In fact, for the smaller values of x, the transition probability into the sterile neutrinos can, even, be larger than the electron neutrino survival probability.

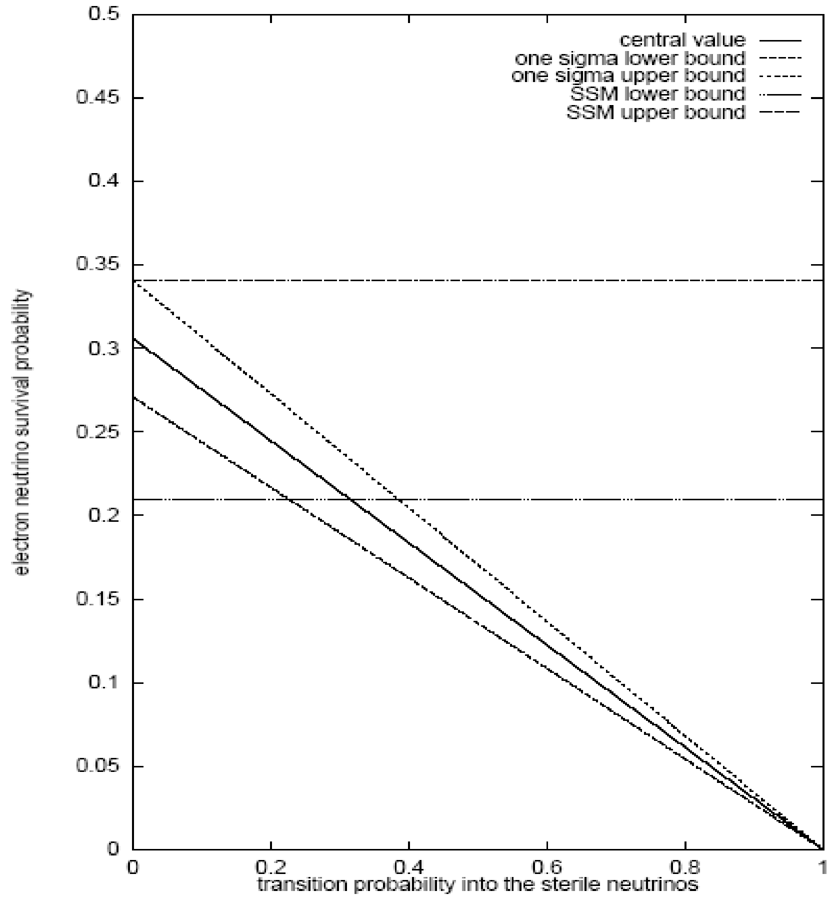

Fig.1. The 1σ allowed region in the P_{ee} –P_{es} space

It is, also, clear from Figure 2, that the errors in the value of x are the most significant sources of error in the values of the probabilities and once the value of x is settled by the experiments, the errors in the probabilities will become much smaller.

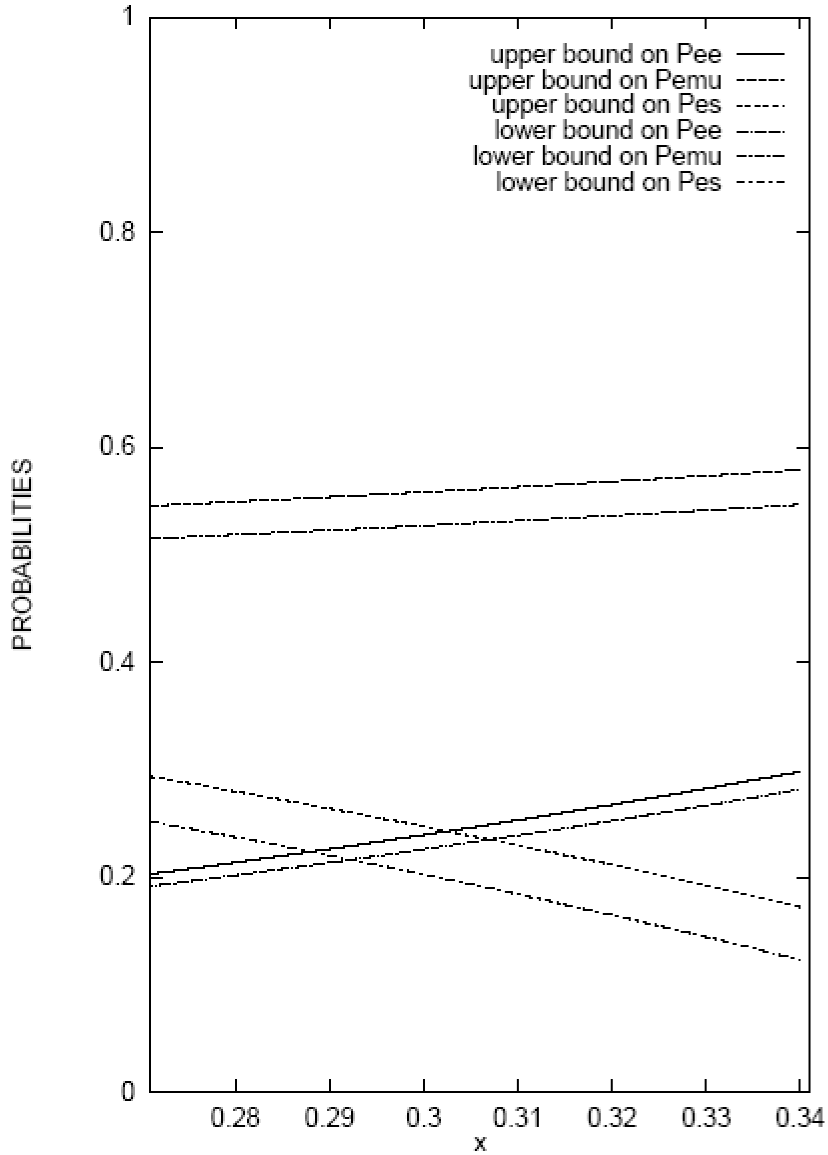

Fig.2. P_{ee}, $P_{e\mu}$ and P_{es} as a function of x.

For example, for a most conservative choice of x = 0.341, the transition probability into the sterile neutrinos is found to be $0.146^{+0.040}_{-0.033}$ which is non zero at 4.4σ C.L. If the value of x is settled below this value (i.e. x ≤ 0.341, as is most likely) by the experiments, the transition probability into the sterile neutrinos as well as the corresponding confidence level will be larger than the above values (at x = 0.341). Thus, the main source of error in the transition probability into the sterile neutrinos being the uncertainty in the value of x, a more precise determination of the value of x (below the value 0.341) will give a non-zero value of P_{es} at more than 4.4 standard deviations.

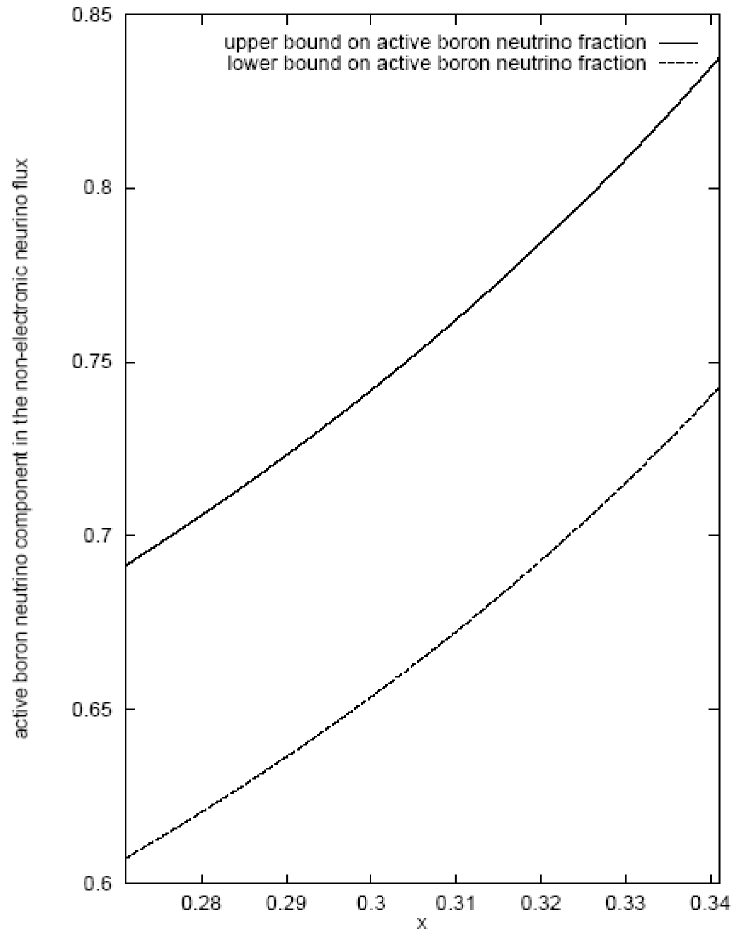

Fig.3. $sin^2\varphi$ as a function of x

From eq. (3.16) and (3.17),one obtains

$$\sin^2\varphi=\frac{(1-x)(\cos^2\theta-P_{LMA})}{\cos^2\theta-x(1+\cos^2\theta-P_{LMA}} \quad (3.25)$$

$$f_B=R_{NC}\,\frac{\cos^2\theta-x}{\cos^2\theta-P_{LMA}} \quad (3.26)$$

where f_B and R_{NC} are the boron neutrino flux and SNO NC flux normalized to the central SSM boron neutrino flux, respectively. The ($f_B - \sin^2\varphi$) degeneracy is, thus, lifted by the use of equation(3.3).

In Figure 3, we plot $\sin^2\varphi$(equation (3.24)) as a function of x. The active neutrino fraction, $\sin^2\varphi$increases with the increase in the SNO CC flux and decrease in the SNO NC flux. Thus, the sterile fraction in the active solar boron neutrino flux, $\cos^2\varphi$, will be larger if the forthcoming measurements at SNO favor smaller values of CC flux and larger values of NC flux. For x=0.341, $\sin^2\varphi = 0.713^{+0.125}_{-0.107}$ and $f_B = 0.114^{+0.29}_{-0.23}$

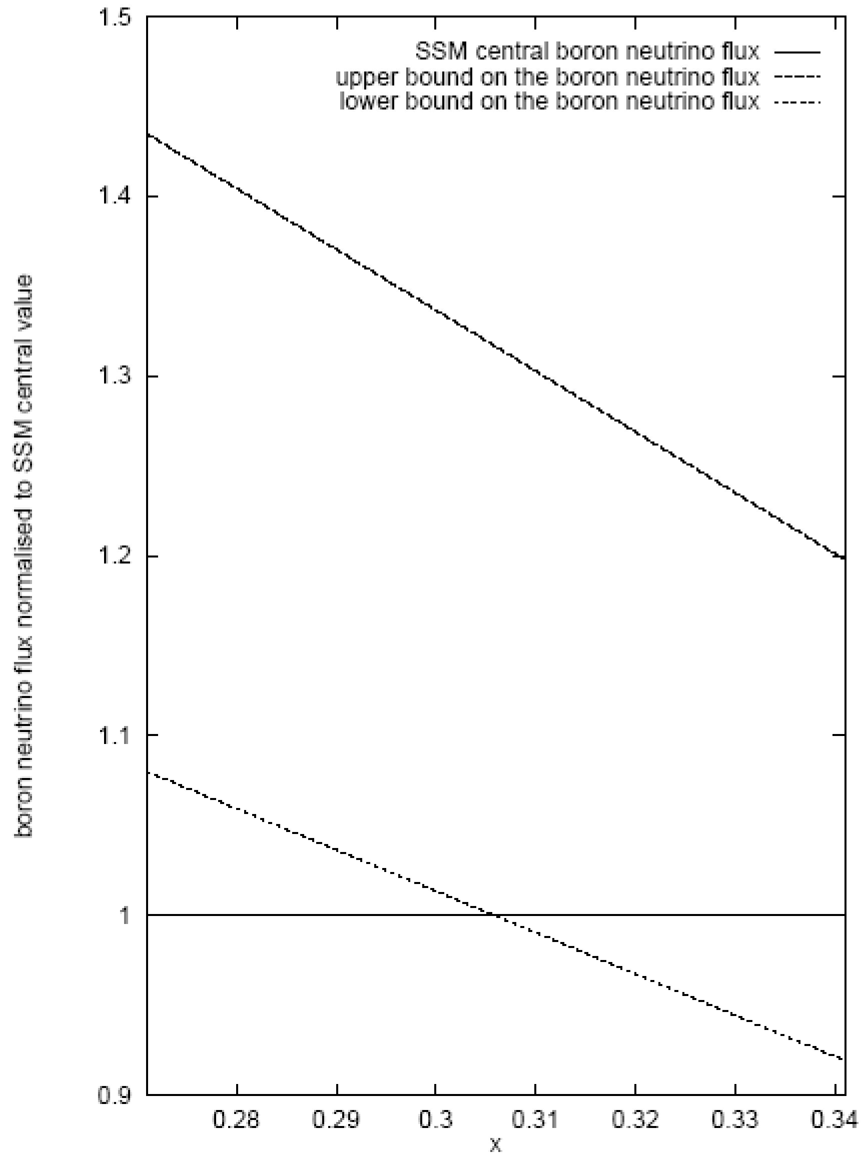

Fig.4. f_B as a function of x

Thus the sterile fraction in the boron neutrino flux is non-zero at about 2.3σC.L**.** indicating oscillation of boron neutrinos into sterile states in the current SNO data. The behavior of $\sin^2 \phi$ with x in the present work is different from that reported by Balentekin et al. [11] by identifying P_{ee} with P_{LMA} and substituting the numerical value of $P_{LM\ A}$ obtained in the pure LMA scenario. However, as discussed earlier, such an approach can not be used to derive meaningful constraints on the sterile fraction.

The boron neutrino flux obtained from equation (3.25) has been plotted as a function of x in Figure 4. Most of the 1σ region of the boron neutrino flux lies above its central value in the SSM in contradiction with the value of boron neutrino flux in the pure LMA scenario.

3.3.Conclusions

In conclusion, the prospects for constraining the sterile neutrino fraction in the born neutrino flux reaching the earth have been examined in a scenario discussed by Hollanda and Smirnov [15] to overcome some generic problems of the LMA scenario. The indications for the presence of sterile component in the boron neutrino flux in the light of the latest SNO salt phase data

and the 766.3 Ty KamLAND data are found to be strong enough to be taken seriously. A precise determination of the CC and NC fluxes at SNO within the present 1σ range gives a transition probability into sterile states which is non-zero at more than 4.4σ. It is found that the sterile component in the boron neutrino flux could be as large as the electron neutrino flux for the present central values of SNO CC and NC fluxes. If the future measurements at SNO yield smaller values of CC/NC flux ratio, the sterile fraction will be, further, enhanced. Thus, there are strong indications of a sterile presence in the boron neutrino flux reaching the detectors on the earth but it will require a precise determination of CC and NC fluxes to pass a final judgment [18]

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4.SUMMARY

Neutrino Physics is passing through a phase of spectacular development. Vast amount of solar and atmospheric neutrino data has been accumulated and the neutrino deficits have been established to be the consequence of non-standard neutrino physics. The most recent steps in this direction are the pioneering results from SNO and KamLAND experiments. The SNO experiment provided a model independent proof of solar neutrino oscillations and the terrestrial disappearance of reactor$\overline{\nu_e}$ in the KamLAND experiment has provided a further confirmation of the neutrino oscillation solution of the solar neutrino problem (SNP). This gives us confidence in the oscillation solution of the atmospheric neutrino anomaly.

The neutral current measurements at SNO have, conclusively, established the oscillations of solar neutrinos. After the evidence of terrestrial antineutrino disappearance in a beam of electron antineutrinos reported by KamLAND , all other

[16] explanations of the solar neutrino deficit can, at best, be just subdominant effects. After these pioneering experiments, there is no scope for doubting the physical reality of neutrino mass and the consequent oscillations. KamLAND is the first experiment to explore the neutrino parameter space relevant to SNP with a beam of terrestrial neutrinos and has, convincingly, demonstrated the existence of neutrino oscillations confined to large mixing angle LMA region.The total event rate as well as the spectrum distortion at KamLAND are in good agreement with the LMA expectations. Recently, updated analyses of all the available solar and reactor neutrino data including KamLAND and SNO salt phase data have been presented. However, even after the confirmation of the LMA MSW mechanism as a dominant solution of SNP, the oscillation parameters are not precisely known. A precise determination of these parameters will be of great importance for theory as well as phenomenology of neutrino oscillations in particular and particle physics in general.

The solar neutrino experiments have, already, entered a phase of precision measurements for oscillation parameters. On the other hand, the LMA solution is facing a deeper scrutiny. In fact, the completeness of the LMA solution is being questioned and the scope for some possible subdominant transitions is being explored vigorously. Does the LMA solution satisfactorily explain all the solar neutrino data? Are there any observations indicating new physics beyond LMA? These are some of the relevant questions being posed. It is also the high time to put the LMA predictions to closer experimental scrutiny. There are, at least, two generic predictions of LMA which point towards life beyond LMA. One of these is the prediction of a high argon production rate, $Q_{AR} \approx$ 3SNU, for the Homestake experiment which is about 2σ above the observed rate. Another generic prediction of the LMA scenario is the 'spectral upturn' at low energies. Within the LMA parameter space, the survival probability should increase with decrease in energy and for the best fit point, the upturn could be as large as 10-15% between 8MeV and 5MeV. However, neither the SuperKamiokande (SK) nor SNO have reported any statistically significant 'rise-up' in the observed neutrino survival probability. Both these predictions of LMA can only be tested in the forthcoming phase of high precision measurements in the solar neutrino experiments and are crucial for confirmation of the LMA solution.

The distortions in the neutrino spectrum are an important factor in resolving the solar neutrino problem. These distortions arise due to the energy dependence of the survival probability as a result of which neutrinos with diﬀerent energies survive in diﬀerent propor-tions leading to distortions in the observed spectrum. Experimentally, the boron neutrinos are the most accessible source for the study of the distortions in the observed spectrum since the SK and SNO detect the boron neutrinos in the small energy bins over a wide energy range. Since, the LMA has emerged as a solution of the

SNP, the spectrum distortions within the LMA scenario are of paramount importance for the final confirmation of the LMA as a solution of the SNP and, also, for possible physics beyond LMA.

The SNO and KamLAND experiments have played a crucial role in resolving the longstanding solar neutrino problem in terms of large mixing angle (LMA) MSW oscillations and are expected to play an important role in the refinement of the LMA solution which is undergoing a deeper scrutiny. Does the LMA solution explain all the solar neutrino data satisfactorily? There are, at least, two generic predictions of LMA indicating new physics beyond LMA. One of these is the prediction of the high argon production rate for Homestake experiment which is about 2σ above the observed rate. Another generic prediction of the LMA scenario is the 'spectral upturn' at low energies. Within the LMA parameter space, the survival probability should increase with decrease in energy and for the best fit parameters, the upturn could be as large as 10-15% between 8 MeV and 5 MeV . In fact, the spectral upturn at low energies is expected to increase further with the KamLAND 766.3 Ty spectral data favoring a larger value of Δm^2.However, neither SuperKamiokande nor SNO has reported any statistically significant 'rise-up' in the observed neutrino survival probability. Both these predictions of the LMA solution can, only, be tested in the forthcoming phase of high precision measurements in the solar neutrino experiments and are crucial for the final confirmation of the LMA solution.

Another unresolved issue is whether the solar neutrinos oscillate into the sterile component. The main motivation for postulating the existence of the sterile neutrino species comes from the LSND experiment which reported a significant $\overline{\nu_{\mu}} \rightarrow \overline{\nu_{e}}$ oscillation probability which requires a new mass scale. Since, the Z-decay width constrains the number of weakly interacting light neutrino species to be very close to three , one is forced to postulate a sterile neutrino. While the purely sterile oscillation solution is excluded at 7.6σ, the solar electron neutrinos could still oscillate into both active and sterile neutrinos, a scenario which is, largely, unconstrained at present. In fact, a combined analysis of solar and atmospheric neutrino data has shown that the active-sterile admixture can take any value between zero and one. While the SNO charged current data excluded the maximal mixing to sterile neutrinos at 5.4σ , arbitrary active-sterile admixtures were not considered. Consequently, a significant sterile fraction in the solar neutrino flux reaching the earth is, still, possible. The discovery of the sterile neutrinos would be of great importance for particle physics, even though, it is, still, not clear how these hypothetical 'exotic' degrees of freedom would fit into elementary particle theory.

The possibility of subdominant transitions into sterile neutrino states accompanying the dominant LMA flavor transitions has been examined earlier and upper bounds on the sterile neutrino fraction in the non-electronic boron neutrino flux have been derived. How-ever, the subdominant transitions into sterile states have neither been confirmed nor ruled out at a statistically significant level. In the present work, the possibility of flavor transitions into sterile component in the solar boron neutrino flux has been examined in a model pre-sented by Hollanda and Smirnov to lower the abnormally high argon production rate in the Homestake experiment and, also, to lower the 'spectral upturn' in the low energy boron neutrino spectrum predicted in the LMA scenario.

The 'rise-up' in the boron neutrino spectrum at low energies has been stud-ied within the framework of the LMA scenario. Indirect bounds on the rise-up have been obtained from the available solar neutrino data. These bounds have been used to demon-strate as to how a precision measurement of the rise-up can be used to further constrain the neutrino parameter space allowed by the SNO salt phase data. It is found that the pure LMA solution is sufficient to explain the SNO salt phase data for $\Delta m^2 \leq 7.9 \times 10^{-5}$ eV^2 and $\theta \leq 33.7^o$ since larger value of Δm^2 will violate the upper bound in eq.(2.26). However, the most recent global analyses of the solar neutrino and the recent KamLAND data favor a value of Δm^2 which violates this upper bound.

Consequently, pure LMA solution seems to be disfavored and other subdominant transitions seem unavoidable. The theoretical and experimental values of the boron neutrino survival probability in the pure LMA scenario for the most recent LMA parameters diﬀer by two standard deviations. This discrepancy is too large to be explained by the subdominant SFP transitions into antineutrinos. In the present work, this discrepancy has been attributed to the subdominant transitions into the sterile neutrinos. It is concluded that the sterile neutrino flux in this scenario could be as large as 0.299 times the boron neutrino flux at 3σ.

The prospects for constraining the sterile neutrino fraction in the born neutrino flux reaching the earth have been examined in a scenario discussed by Hollanda and Smirnov to overcome some generic problems of the LMA scenario. The indications for the presence of sterile component in the boron neutrino flux in the light of the latest SNO salt phase data

and the 766.3 Ty KamLAND data are found to be strong enough to be taken seriously. A precise determination of the CC and NC fluxes at SNO within the present 1σ range gives a transition probability into sterile states which is non-zero at more than 4.4σ. It is found that the sterile component in the boron neutrino flux could be as large as the electron neutrino flux for the present central values of SNO CC and NC fluxes. If the future measurements at SNO yield smaller values of CC/NC flux ratio, the sterile fraction will be, further, enhanced. Thus, there are strong indications of a sterile presence in the boron neutrino flux reaching the detectors on the earth but it will require a precise determination of CC and NC fluxes to pass a final judgment.