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Neutrino oscillations: Recent results and future directions

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Abstract. A brief introduction to the phenomena of vacuum neutrino oscillations and resonant flavour conversion is presented with a heavy pedagogic leaning. Variants of these ideas, e.g., neutrino helicity flip in a magnetic field, violation of the equivalence principle, etc. are outlined. A few vexing issues pertaining to the quantum mechanics of neutrino oscillations are discussed. Expectations from some of the future experiments are summarized.

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1. Introduction

The recent announcement by the super-Kamiokande collaboration of evidence of neutrino oscillations in their atmospheric neutrino data has added a new impetus to the attempts to unravel the mysteries of neutrino mass and its manifold impact in particle physics, astrophysics, and cosmology. Several of the previous speakers at this discussion meeting have touched upon the ideas of neutrino mass and oscillations which makes my job a lot easier. Before embarking on the presentation, an apology is due for the lack of adequate and up-to-date referencing. Fortunately, much of the details and current developments can be traced on the internet [1].

2. Oscillations in vacuum

The idea of neutrino oscillations [2] is rooted in quantum mechanics. The time evolution of a stationary state $|\psi_k\rangle$ (in units such that $\hbar = c = 1$) is:

$$|\psi_k(t)\rangle = |\psi_k\rangle \ \ \exp\,(-i\ E_k t), \tag{1}$$

where E_k is the energy eigenvalue corresponding to $|\psi_k\rangle$. Thus, the stationary state vectors at different times differ simply by an overall phase change. The time evolution of an arbitrary, i.e., non-stationary, state, $|\psi\rangle$, is more complicated. For such a state we can write at $t = 0$:

$$|\psi(0)\rangle = \sum_k a_k \, |\psi_k\rangle, \tag{2}$$

where a_k are constants. Using eq. (1) one finds:

$$|\psi(t)\rangle = \sum_k a_k \, |\psi_k\rangle \, \exp\,(-iE_k t). \tag{3}$$

For neutrinos, the basic assumption is that the familiar electron and muon neutrinos (ν_e and ν_μ) – which are often termed *flavour* eigenstates – are not the mass eigenstates (i.e., the stationary states) ν_1 and ν_2, but their superpositions:

$$|\nu_e\rangle = |\nu_1\rangle \, c \, + \, |\nu_2\rangle \, s; \quad |\nu_\mu\rangle = -|\nu_1\rangle \, s \, + \, |\nu_2\rangle \, c \tag{4}$$

where $c = \cos\theta$ and $s = \sin\theta$. For two flavours a single angle, θ, suffices to completely specify one basis in terms of the other. Consider now the state vector of a ν_e produced at $t = 0$. Thus, initially $|\psi(0)\rangle = |\psi_{\nu_e}\rangle = c|\psi_1\rangle + s|\psi_2\rangle$. If the stationary states $|\psi_1\rangle$ and $|\psi_2\rangle$ correspond to energies E_1 and E_2, respectively, then at a later time the state vector will be:

$$|\psi(t)\rangle = c|\psi_1\rangle \, \exp(-iE_1 t) \, + \, s|\psi_2\rangle \, \exp(-iE_2 t). \tag{5}$$

The probability, $P(\nu_e, 0; \nu_\mu, t)$, of the state $|\psi(t)\rangle$ (originating as a ν_e at $t = 0$) appearing as a ν_μ is $|\langle\psi_{\nu_\mu}|\psi(t)\rangle|^2$ and can be expressed as:

$$P(\nu_e, 0; \nu_\mu, t) = c^2 s^2 |\, - \exp(-iE_1 t) \, + \, \exp(-iE_2 t)|^2. \tag{6}$$

The neutrinos are expected to have small masses, m_i, and are in the ultra-relativistic regime ($E_i \simeq p + m_i^2/2p$) where p ($\gg m_i$) is the magnitude of the neutrino momentum. In this situation:

$$P(\nu_e, 0; \nu_\mu, t) = 4c^2 s^2 \sin^2\left(\frac{\Delta m^2}{4p} t\right) = \sin^2 2\theta \sin^2\left(\frac{\pi x}{\lambda}\right), \tag{7}$$

where $\Delta m^2 = m_2^2 - m_1^2$ and

$$\lambda = \frac{4\pi p}{\Delta m^2} \tag{8}$$

is the so-called *oscillation length*. In the right hand side of eq. (7) the first factor is a consequence of the 'mixing' while the second factor leads to the 'oscillatory' behaviour. In the vacuum oscillation case, the first factor, dependent on the mixing angle θ, is a constant but in the Mikheyev–Smirnov–Wolfenstein (MSW) matter effect, discussed next, it changes with the matter density.

From eq. (7)

$$P(\nu_e, 0; \nu_e, t) = 1 - P(\nu_e, 0; \nu_\mu, t) = 1 - \sin^2 2\theta \sin^2\left(\frac{\pi x}{\lambda}\right). \tag{9}$$

It is seen from the above that $P(\nu_e, 0; \nu_e, t)$ can be less than or equal to unity. The essential ingredients for this are twofold:

1. The neutrinos must be massive and non-degenerate.
2. The mass eigenstates of the neutrinos – $\nu_1, \ \nu_2$ – must be different from the flavour eigenstates – $\nu_e, \ \nu_\mu$.

3. Variants

3.1 *Matter effects*

Of the variants of this basic theme of neutrino flavour change the most prominent is the Mikheyev–Smirnov–Wolfenstein (MSW) [3] matter induced resonant effect. The mass square matrix for the two-neutrino system in the flavour basis is:

$$M_f^2 = \left(\frac{m_1^2 + m_2^2}{2}\right) I \; + \; \frac{1}{2}\begin{pmatrix} -\Delta m^2 \cos 2\theta_V & \Delta m^2 \sin 2\theta_V \\ \Delta m^2 \sin 2\theta_V & \Delta m^2 \cos 2\theta_V \end{pmatrix}, \qquad (10)$$

where I stands for the 2×2 identity matrix. It is easy to check that M_f^2 is diagonalized by the orthogonal matrix characterized by the neutrino mixing angle – denoted here by θ_V. The average mass squared, $(m_1^2 + m_2^2)/2$, plays no rôle in our discussion of neutrino oscillations; only the difference in mass^2, Δm^2, and the mixing angle, θ_V, are of relevance here.

The MSW effect originates from the additional interactions of a neutrino in a medium which result in a varying mass akin to the effective mass of an electron moving in a solid. The most well-known application of the MSW mechanism has been to the case of solar neutrinos where the ν_e, produced in the interior by fusion reactions, on their way out must pass through dense regions of the sun. Both charged and neutral weak interactions with the material can contribute to the effective mass. However, since the solar neutrinos typically carry an energy of a few MeV while the muon's mass is ~ 105 MeV, the charged current interaction for the ν_μ – i.e., $\nu_\mu + e^- \to \nu_e + \mu^-$ – is kinematically forbidden. The upshot of this is that through neutral current interactions ν_e and ν_μ receive the same contributions to the mass terms – adding to the irrelevant term proportional to the identity in eq. (10) – while the charged current contributes only to ν_e. As a consequence, in place of eq. (10) we now have:

$$M_{\rm MSW}^2 = \left(\frac{m_1^2 + m_2^2}{2} + \delta_{\rm nc}\right) I + \frac{1}{2}\begin{pmatrix} -\Delta m^2 \cos 2\theta_V + 2\delta_{\rm cc} & \Delta m^2 \sin 2\theta_V \\ \Delta m^2 \sin 2\theta_V & \Delta m^2 \cos 2\theta_V \end{pmatrix} \qquad (11)$$

with $\delta_{\rm cc} = 2\sqrt{2} G_F n_e(r) E$, where $n_e(r)$, the number density of electrons, is a function of the distance from the solar centre, r. The mixing angle obtained from (11) is:

$$\theta = \frac{1}{2} \arctan\left(\frac{\Delta m^2 \sin 2\theta_V}{\Delta m^2 \cos 2\theta_V - \delta_{cc}}\right). \qquad (12)$$

It is important to bear in mind that both θ and the oscillation length λ are now functions of the energy.

Two cases are distinguished:

(A) *The adiabatic case*: If

$$\frac{{\rm d}\theta}{{\rm d}r} \ll \frac{1}{\lambda} \qquad (13)$$

i.e., the change in the mixing angle is small over one oscillation length, then the usual adiabatic approximation of quantum mechanics is valid: an eigenstate adjusts as the Hamiltonian changes gradually. If an electron neutrino is produced in a region of the sun where the mixing angle is θ and later detected on earth (mixing angle θ_V) then

$$P(\nu_e, 0; \nu_e, t) = \sum_{i=1}^{2} |\langle \nu_e | (\nu_i)_{\rm earth} \rangle \langle (\nu_i)_{\rm sun} | \nu_e \rangle|^2$$
$$= [1 + \cos 2\theta_V \cos 2\theta]/2. \tag{14}$$

Interference terms average out to zero once integrations over the production region (the size of the sun) and the detector size are performed.

(B) *The non-adiabatic case*: Here

$$\frac{{\rm d}\theta}{{\rm d}r} \gg \frac{1}{\lambda} \tag{15}$$

This is a situation where the change in the mixing angle is very rapid and there is a 'jumping probability' from one eigenstate to another ($\nu_1 \leftrightarrow \nu_2$). A resonance point is defined from eq. (12) by $\delta_{cc} = \Delta m^2 \cos 2\theta_V$. In terms of the number density of electrons at resonance, $(n_e)_{\rm res}$, the jumping probability, X, can be written as:

$$X = \exp\left[-\frac{\pi}{4}\frac{\Delta m^2}{E}\frac{\sin^2 2\theta_V}{\cos 2\theta_V}\frac{1}{|\frac{{\rm d}\ \ln n_e}{{\rm d}r}|_{\rm res}}\right]. \tag{16}$$

Strictly speaking, the above expression is valid when the number density n_e varies linearly with r near the resonance point. In the non-adiabatic case the electron neutrino survival probability (see eq. (14)) is:

$$P(\nu_e, 0; \nu_e, t) = [1 + (1 - 2X)\cos 2\theta_V \cos 2\theta]/2. \tag{17}$$

3.2 *Neutrino helicity flip in a magnetic field*

The precession of the spin of the neutrino in an ambient (e.g., solar) magnetic field [4] can also deplete the signal since it can transform a left-handed neutrino to a right-handed one and the latter – not a participant in the weak interactions – will escape the detector. This possibility can be illustrated through the $\nu_{\rm L} - \nu_{\rm R}$ mass square matrix:

$$M_f^2 = \left(\frac{m_{\rm L}^2 + m_{\rm R}^2}{2}\right) I + \frac{4E}{2}\begin{pmatrix} \Delta_{\rm LR}/4E & \mu B \\ \mu B & -\Delta_{\rm LR}/4E \end{pmatrix}, \tag{18}$$

where $\Delta_{\rm LR} = m_{\rm L}^2 - m_{\rm R}^2$, while B and μ are the magnitudes of the external magnetic field and the neutrino magnetic moment. The oscillation parameters following from eq. (18) are:

$$(\tan 2\theta)_{\rm eff} = \frac{4\mu BE}{\Delta_{\rm LR}}; \quad \left(\frac{\Delta}{4E}\right)_{\rm eff} = \left[\left(\frac{\Delta_{\rm LR}}{4E}\right)^2 + \mu^2 B^2\right]^{1/2}. \tag{19}$$

Notice that $\nu_{\rm L}$ oscillates to $\nu_{\rm R}$ through this mechanism. Variants of this basic idea have considered matter effects in conjunction with spin precession, $(\nu_e)_{\rm L} \leftrightarrow (\nu_\mu)_{\rm R}$ oscillations mediated by transition magnetic moments, etc. The magnitude of the magnetic moment required ($\mu \sim 10^{-10}\mu_B$) for the effect to be significant for typical solar neutrino energies is rather high and much ingenuity was called for in building models satisfying, at the same time, the tight constraints from the smallness of the neutrino mass. The early Homestake solar neutrino data could be interpreted as signaling an anticorrelation with the solar magnetic activity, which fits in well with this picture. However, the statistics was not compelling to start with and, further, the Kamiokande results do not support it.

3.3 *Violation of the equivalence principle*

Another mechanism which can lead to neutrino oscillations is through violation of the equivalence principle [5]. Assume that the neutrino states with a diagonal coupling to gravity, ν_1 and ν_2, are superpositions of the states of definite flavour:

$$|\nu_1\rangle = |\nu_e\rangle\ \cos\theta_G\ +\ |\nu_\mu\rangle\ \sin\theta_G; \qquad |\nu_2\rangle = -|\nu_e\rangle\ \sin\theta_G\ +\ |\nu_\mu\rangle\ \cos\theta_G. \tag{20}$$

In the $\nu_1 - \nu_2$ basis

$$H = \begin{pmatrix} E|\phi(r)|f_1 & 0 \\ 0 & E|\phi(r)|f_2 \end{pmatrix}. \tag{21}$$

Here $|\phi(r)|$ is the Newtonian gravitational potential and $\Delta f = f_1 - f_2$ is a measure of the violation of the equivalence principle. From eqs (20), (21) it is straightforward to obtain the time evolution of a ν_e and one finds that the factor $\Delta m^2/2E$ appearing in the expression for the vacuum oscillation probability gets replaced by $2E|\phi(r)|\Delta f$. The key point is the consequent different energy dependence of the oscillation probability. Experimental data can be used to set tight constraints on θ_G and Δ_f [6].

3.4 *Three generations*

The LEP result that there are three light neutrinos is also supported by the requirements of nucleosynthesis in the early universe. In a realistic three-flavour framework it is important to perform a combined analysis to find the allowed range of parameters. In particular, this might uncover regions in the parameter space sensitive to the presence of the third generation which cannot be probed in the two-flavour limit.

The general expression for the probability that an initial ν_α of energy E gets converted to a ν_β after travelling a distance L in vacuum is

$$P_{\nu_\alpha\nu_\beta} = \delta_{\alpha\beta} - 4\,\Sigma_{j\rangle i}\,U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}\sin^2\left(\frac{\pi L}{\lambda_{ij}}\right). \tag{22}$$

where $\lambda_{ij} = 2.47m(E_\nu/\mathrm{MeV})(\mathrm{eV}^2/\Delta_{ij})$, $\Delta_{ij} = {m_j}^2 - {m_i}^2$. The actual forms of the various survival and transition probabilities depend on the spectrum of Δ_{ij} assumed and

the choice of the mixing matrix U relating the flavour eigenstates to the mass eigenstates. Assuming no CP-violation in this sector, U can be parametrized in terms of three mixing angles [7].

3.5 *Sterile neutrinos*

In many extensions of the standard model there are additional neutrinos, singlets under the electroweak gauge group, immune to the usual strong, weak and electromagnetic interactions. Mixing of such *sterile* neutrinos with the *sequential* ones has also been widely examined. In radiochemical solar neutrino experiments the sterile neutrinos, just as the ν_μ or ν_τ, will not be detected. In Čerenkov detectors both charged and neutral weak interactions of neutrinos contribute. The ν_e contributes through both, the ν_μ only through the latter while sterile neutrinos do not interact at all. Sterile neutrinos have been of more interest of late since the solar neutrino results, the atmospheric neutrino anomaly and the LSND results, if interpreted in terms of neutrino oscillations require very different Δm^2. This necessitates four nondegenerate neutrino states [8]. Since the LEP data does not permit more than three generations of sequential light neutrinos, the fourth state in this picture is usually chosen to be sterile.

4. Matters of principle

New experimental results supportive of neutrino oscillations have also encouraged a renewed interest in a closer analysis of matters of principle, often overlooked, pertaining to this issue. Some of these are:

1. The evolution of mass eigenstates in space and time dictated by quantum mechanics is summarized by the equation

$$|\nu_i(\vec{x},t)\rangle = |\nu_i(0,0)\rangle\, \mathrm{e}^{i(\vec{p_i}.\vec{x}-E_i t)}, \tag{23}$$

where the energy, E_i, and momentum, $\vec{p_i}$, are related by

$$E_i^2 = \vec{p_i}^{\,2} + m_i^2. \tag{24}$$

Two alternatives often appear in the literature regarding the energy and momenta of the two mass eigenstates produced in a process. Indicating by p_i the magnitude of $\vec{p_i}$, these are:

(a) Choose $p_1 = p_2 = p$ implying $\Delta E = E_1 - E_2 = (m_1^2 - m_2^2)/2p$,
(b) Choose $E_1 = E_2 = E$ implying $\Delta p = p_1 - p_2 = (m_1^2 - m_2^2)/2E$.

(a) and (b) yield the same physics results. Nonetheless, it needs to be decided which of these is the proper one to use. In view of the fact that the uncertainty of the production point in all cases of interest, as determined by the size of the source, is much smaller than the oscillation wavelength, the momentum uncertainty permitted

by quantum mechanics can be larger than the momentum splitting considered in (b). On the other hand, the uncertainty in the time of emission is less clear cut and can be large. According to this line of thinking, it is preferable to choose the two states to have the same energy – i.e., alternative (b) – rather than the same momentum – alternative (a).

2. In discussions of neutrino oscillations, the mass eigenstates are assumed to be ultra-relativistic. What if this is not the case? What if one of the states is ultra-relativistic and the other is not? In the latter case, coherence will be lost rapidly but effects of mixing would still show up (see below).
3. In the standard analysis of neutrino oscillations it is assumed that though the two mass eigenstates propagate differently, the initial coherence between the states is retained when they are detected at a distant detector. Is this assumption truly valid in all cases? Obviously, coherence will be retained over short distances compared to the length scale of the problem, namely, the oscillation length. The assumption is questionable for traversal distances large compared to the oscillation length when due to the different masses of the two eigenstates and the consequent different velocities the two will begin to separate. To address this question, note that in the usual analysis one uses

$$\begin{aligned} P(\nu_e, 0; \nu_\mu, t) &= |\langle \nu_\mu|\nu_1\rangle \cos\theta \mathrm{e}^{-iE_1 t} + \langle \nu_\mu|\nu_2\rangle \sin\theta \mathrm{e}^{-iE_2 t}|^2 \\ &= \cos^2\theta \sin^2\theta \; 4\sin^2 \frac{(E_1 - E_2)t}{2} \\ &= \sin^2 2\theta \sin^2 \frac{\pi L}{\lambda}. \end{aligned} \tag{25}$$

On the other hand, if the two mass eigenstates are no longer coherent then the *probabilities* must be summed, *not the amplitudes*, and one has

$$\begin{aligned} P(\nu_e, 0; \nu_\mu, t) &= |\langle \nu_\mu|\nu_1\rangle \cos\theta \mathrm{e}^{-iE_1 t}|^2 + |\langle \nu_\mu|\nu_2\rangle \sin\theta \mathrm{e}^{-iE_2 t}|^2 \\ &= 2\cos^2\theta \sin^2\theta \\ &= \frac{1}{2}\sin^2 2\theta. \end{aligned} \tag{26}$$

Now, in the $L \gg \lambda$ limit, in the usual formulation, (eq. (25)), the average of the length dependent factor ($= 1/2$) is used and this gives the same result as the incoherent case (eq. (26)).

4. *Moving sources and detectors*: In most situations considered, there are two length scales involved, viz. the oscillation length λ and the distance from the source to the detector L. In this meeting, it has been stressed [9] that in situations where the source and/or the detector is not at rest, the distance traveled by them is a third one. So far, such a situation obtains only for the LSND experiment. Even there, the $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation uses μ^+ decays at rest (DAR) and it is only for the $\nu_\mu - \nu_e$ oscillations studied using decays in flight (DIF) that the question is pertinent. However, it is easy to ascertain that the third distance, namely, the uncertainty in the point of origin due to the decay position, is small compared to the oscillation length even in this case. Nonetheless, this is a question of principle which does not appear to have been satisfactorily looked into.

5. Future experiments

Before embarking on a discussion of some of the upcoming experiments, let us look back in history and recall that there was a claimed evidence of neutrino oscillation in a reactor experiment as early as in 1980 [10]. In this experiment $\bar{\nu}_e$ from a 2000 MW reactor were detected at distances of 6 m and 11.2 m through CC and NC scattering off deuterons in heavy water as well as via inverse beta decay. In a two flavour analysis, the results indicated a preferred range of $0.5 \leq \sin^2\theta \leq 0.8$ and 0.7 eV$^2 \leq \Delta m^2 \leq 1$ eV^2. Unfortunately, the statistics was not compelling and this region of parameter space has been ruled out by the more recent results from Bugey. The message that comes through is that neutrino experiments are notoriously difficult and confirmation of every result by a second independent experiment is a must.

There are many experiments being prepared to test different ranges of neutrino mass and mixing in the future. We now briefly list some of them.

1. *Super-Kamiokande*: Super-Kamiokande is, of course, running and has already presented results of great importance. More high statistics results are eagerly awaited from it for both the atmospheric and solar neutrinos. This is expected to throw light on issues like (a) Seasonal variations of the solar neutrino flux indicative of the vacuum oscillation solution, (b) day–night effect of solar neutrinos which will enable a distinction between the large and small angle MSW solutions, (c) spectral shape deformation of solar neutrinos as a normalization independent check on neutrino oscillations, etc. It will also serve as a telescope for neutrinos from a supernova explosion.

2. *Sudbury Neutrino Observatory (SNO)*: This experiment will use 1 kton of D_2O surrounded by 7.3 ktons of ordinary water. Neutrinos will be detected by: (a) CC disintegration $\nu_e + d \to e^- + p + p$ through the Čerenkov radiation from the electron, (b) NC disintegration $\nu + d \to \nu + n + p$ to be detected calorimetrically by the γ emission on neutron capture, and (c) CC and NC scattering $\nu + e^- \to \nu + e^-$ again via Čerenkov radiation. Only the ν_e contribute to the CC reactions while sequential neutrinos of all three flavours contribute with equal strength to the NC reactions. Based on the standard solar model, the expected count rates per year for these reactions are 9,750, 2,800, and 1,100 respectively. The neutrino threshold energy at SNO should be about 5 MeV.

3. *Borexino*: This experiment being set up at the Gran Sasso laboratory will look for solar neutrinos using 100 tons of ultrapure liquid scintillator. It will detect a neutrino event using the recoil electron in $\nu - e$ scattering with a threshold *electron* energy as low as 0.25 MeV. It has a real time sensitivity to ^{7}Be neutrinos (the 0.86 MeV line which has about 90% of the emission) from the sun. This is of special importance since (a) the existing experimental results seem to indicate an almost complete suppression of Be neutrinos and (b) all the earlier experiments sensitive to these neutrinos were radiochemical in nature. Based on the flux predictions of the SSM, 50 events per day are expected at Borexino. The scintillation based detection of this experiment does not provide directional information.

4. *ICARUS*: This 600 ton liquid argon detector is also being set up at the Gran Sasso laboratory. It has a neutrino energy threshold of 4–5 MeV and will hence be sensitive

only to ^{8}B neutrinos from the sun. It will detect neutrinos via (a) the scattered electron in $\nu - e$ scattering which proceeds through both CC and NC interactions and (b) the deexcitation of ^{40}K* produced in the reaction $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$. The ground state of ^{40}K has $J^\pi = 4^-$; hence the deexcitation occurs through the emission of several gammas. The events of type (a) and (b) are distinguished by their angular distributions – (a) is directed along the ν direction while (b) is more isotropic – and multiplicity – (b) has several gammas. Detection of solar neutrinos as well as measurement of the atmospheric neutrino ratio $(\#(\nu_\mu + \bar{\nu}_\mu))/(\#(\nu_e + \bar{\nu}_e))$ is envisaged.

Further in the future (Future^2) there are plans for a 5 kton detector along similar lines. Another possibility is to add 5% of CD_4 (deuterated methane) and look for the CC reaction $\nu_e + d \rightarrow e^- + p + p$. The electron will be isolated while the two protons will produce intense ionization at the vertex. A third plan is to use the facility as a long baseline detector for the NGS (Neutrino to Gran Sasso) beam from CERN.

5. *Homestake iodine experiment*: This is the new setup being planned at Homestake to replace the chlorine experiment and uses the same basic radiochemical principle with the reaction $\nu_e + {}^{127}\mathrm{I} \rightarrow {}^{127}\mathrm{Xe} + e^-$. The ^{127}Xe decays by electron capture with a half-life of 36.4 days. The initial programme is to set up a 100 ton detector which will eventually be increased to 1 kton.

6. *Gallium Neutrino Observatory (GNO)*: This is the upgraded GALLEX experiment which will have 30, 60, and 100 tons of gallium in stages.

7. *Long baseline experiments*: The atmospheric neutrino experiments seem to indicate the occurrence of $\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_s$ oscillations with a mass^2 splitting around $10^{-2} - 10^{-3}$ eV^2. Since accelerators provide ν_μ beams of higher energy, in order to probe this favoured mass difference range using these neutrinos one must have long baselines of several hundreds of kilometres. A number of such experiments are in the planning stages:

   - *K2K*: Among the long baseline accelerator experiments the one that is in the most advanced stage is K2K using a neutrino beam originating from KEK and detected at super-Kamiokande – a baseline of 250 km. The neutrinos will be produced by delivering a 12 GeV proton beam on target producing a mean beam energy of 1.4 GeV. The ν_e contamination is expected to be about 1%. A fourteen-fold increase in the neutrino flux is achieved by focusing the positively charged particles at the target by a toroidal magnetic field. The experiment plans to look for an excess of ν_e as also a distortion of the ν_μ spectrum by comparing with a near detector. With the limited energy of the beam, $\nu_\mu \leftrightarrow \nu_\tau$ oscillations can be searched for only in the disappearance mode. There are future plans of using 50 GeV protons to produce a neutrino beam of higher energy when $\nu_\mu \leftrightarrow \nu_\tau$ will be looked for using the appearance of τs in the final state.
   - *CERN to Gran Sasso*: The Gran Sasso laboratory with its rock shielding is ideal for neutrino experiments. It is planned to have a neutrino beam to Gran Sasso (NGS) from CERN which will correspond to a baseline of 740 km. Several experiments are planning to take advantage of this beam. They include

the ICARUS facility discussed earlier. Another is the Neutrino Oscillation Experiment (NOE) which plans to use 6.7 ktons of scintillating fibre. They plan to look for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations by searching for τ decays and $\nu_\mu \leftrightarrow \nu_e$ oscillations by measuring any excess of electrons. Disappearance of ν_μ due to oscillations will be gauged from a measurement of the relative strengths of the CC and NC signals. A third experiment under consideration is OPERA which is based on a 1 kton Emulsion Cloud Chamber. This is a hybrid device where emulsion plates alternate with free space and the set up is expected to be sensitive to $\Delta m^2 = 10^{-3}$ eV^2.

- *MINOS*: This is a long baseline experiment being planned with a neutrino beam from Fermilab directed to the SOUDAN setup in Minnesota. The distance from source to detector will be 730 km and the average neutrino energy is expected to be 10 GeV. The experiment will look for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

8. *COSMOS*: This is an accelerator experiment similar in spirit to CHORUS and NOMAD at CERN. With a baseline of 1 km and $\langle E_\nu \rangle$ = 10 GeV, it will look for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

9. *Reactor experiments*: Nuclear reactors are copious sources of $\bar{\nu}_e$ and have been a standard source for neutrino experiments since the fifties. Several experiments to look for oscillations are planned for the future using reactor antineutrinos.

   - *Palo Verde*: This experiment will use scintillation detectors at distances of 750, 888, and 889 metres from the reactor to search for oscillations in the disappearance mode. The relevant reaction is $\nu_e + p \rightarrow e^+ + n$ where the e^+ produces annihilation photons while the neutron is identified by the delayed photon emitted on absorption. The expected sensitivity of this experiment is to $\Delta m^2 > 1.3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.1$.
   - *KAMLAND*: This experiment will use reactor antineutrinos with an average energy of 3 MeV. The baseline is expected to be 100 km and it will search for oscillations in the disappearance mode.
   - *Bugey3, MUNU at Bugey*: These are new experiments planned at the Bugey reactor.

6. Discussions and conclusions

- *Experiments guiding theory*: In this field experiments are guiding theory and this trend will continue with the several new setups in various stages of fabrication and development.
- *Which solution for solar neutrinos*?: The present data for solar neutrinos is consistent with three different possibilities, namely, the small angle MSW solution, the large angle MSW solution, and the vacuum oscillation solution [11]. They may be distinguished by seasonal variations, day–night effect, spectral deformation, etc. and it is hoped that the high statistics, real time data from the new experiments will be very valuable for this.
- $\nu_\mu \leftrightarrow \nu_\tau$ *or* $\nu_\mu \leftrightarrow \nu_s$ *for atmospheric neutrinos*: It is not possible to choose between these two alternatives as solutions to the atmospheric neutrino anomaly on the basis

of present data. Since the ν_τ has neutral current interactions which the sterile ν_s does not, it may be feasible to decide the issue using, for example, the rate of π^0 production in the data. Long baseline accelerator experiments, sensitive to the same region of parameter space, looking for ν_τ in the final state will also help in coming to a conclusion.

- *Pinning down 3-flavour mixing*: Since very different mass splittings are needed to explain the solar neutrino problem and the atmospheric neutrino anomaly in terms of oscillations, it is clear that this would also require mixing between at least three neutrinos. The LSND experiment seems to be indicating yet another mass splitting and if all of these results are taken together then a four neutrino framework will be needed. Even setting aside the LSND result till there is independent confirmation, a comprehensive analysis of all data in the three neutrino scenario is needed for pinning down the masses and mixings in this sector.
- *^{7}Be neutrinos from the sun*: Some of the fits to all the available solar neutrino data seem to indicate a complete absence of ^{7}Be neutrinos. So far, the experiments that are sensitive to these neutrinos – GALLEX, SAGE, and the Homestake chlorine experiment – are all radiochemical in nature. To completely settle this issue a real time experiment sensitive to the ^{7}Be neutrinos is called for. The Borexino experiment will fill in precisely this gap.
- *Independent check of LSND*: Experiments in neutrino physics are notoriously difficult. This very interesting result cries out for independent confirmation. It is hoped that in a few years time the Karmen experiment will be able to either confirm or rule out the LSND result.
- *Long baseline experiments*: The long baseline accelerator experiments will be able to examine regions of parameter space preferred by the oscillation explanation of the atmospheric neutrino data. Several such experiments are in the development stage and results are eagerly awaited.
- *Supernova neutrinos*: Our past experience with neutrinos from the SN1987A supernova gives us confidence that in the event of a similar occurrence in our galaxy, the huge facilities like super-Kamiokande and SNO will observe a clear signal from the neutrinos of the post bounce epoch.
- *Model building*: A parallel line of development is the building of models of neutrino masses. This has been discussed by several speakers [12] in this meeting and is a very rich area of activity.

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