NEUTRINO MASSES AND MIXING

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I review the status of neutrino masses and mixings in the light of the solar and atmospheric neutrino data. The result from the LSND experiment and the possible role of neutrinos as hot dark matter are also included. I also discuss the simplest schemes proposed to reconcile these data which include a light sterile neutrino in addition to the three standard ones. Implications for future experiments are commented.

1. Introduction

Neutrinos are the only massless fermions predicted by the Standard Model (SM). This seems to be a reasonable assumption as none of the experiments designed to measure the neutrino mass in laboratory experiments have found any positive evidence for a non-zero neutrino mass. At present the existing limits from laboratory searches are:

\[
\begin{align*}
    m_{\nu_e} &< 15 \text{ eV} \\
    m_{\nu_\mu} &< 170 \text{ KeV} \\
    m_{\nu_\tau} &< 18.2 \text{ MeV}
\end{align*}
\]

The square of the electron neutrino mass is measured in tritium beta decay experiments by fitting the end point distribution. In several of these experiments there has been found a negative mass squared which is concluded to be due to unknown effects which cause the accumulation of events near the endpoint. This makes the limit above still far from certain. The muon neutrino mass limit is derived from the measurement of the muon neutrino momenta on the decay \(\pi^+ \to \mu^+ \nu_\mu\), while the tau neutrino mass limit given above is based on kinematics of \(\tau\) decays. For a detail discussion on the \(\tau\) neutrino mass limit see [3].

However, the confidence on the masslessness of the neutrino is now under question due to the important results of underground experiments, starting by the geochemical experiments of Davis and collaborators till the more recent Gallex, Sage, Kamiokande and SuperKamiokande experiments [3, 4]. Altogether they provide solid evidence for the existence of anomalies in the solar and the atmospheric neutrino fluxes. Particularly relevant has been the recent confirmation by the SuperKamiokande collaboration [4] of the atmospheric neutrino zenith-angle-dependent deficit which strongly indicates towards the existence of \(\nu_\mu\) conversion. Together with these results there is also the indication for neutrino oscillations in the \(\bar{\nu}_\mu \to \bar{\nu}_e\) channel by the LSND experiment [5]. If one tries to include all these requirements in a single framework, we finds three mass scales involved in neutrino oscillations. The simplest way to reconcile these requirements invokes the existence of a light sterile neutrino i.e. one whose interaction with standard model particles is much weaker than the SM weak interaction so it does not affect the invisible Z decay width, precisely measured at LEP [7]. To this we may add the possible role of neutrinos in the dark matter problem and structure formation [8-10].

2. Indications for Neutrino Mass

2.1. Solar Neutrinos

At the moment, evidence for a solar neutrino deficit comes from four experiments [3], Homestake, Kamiokande, Gallex and Sage experiments. The most recent data on the rates can be summarized as:

| Chlorine | 2.56 ± 0.23 SNU |

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Figure 1. Presently allowed MSW solar neutrino parameters for 2-flavour active neutrino conversions with an enhanced \textit{hep} flux, from Ref. \cite{15}.

| Experiment       | Parameter                      |
|------------------|--------------------------------|
| Gallex and Sage  | $72.2 \pm 5.6$ SNU             |
| Superkamiokande  | $(2.44 \pm 0.10) \times 10^6$ cm$^{-2}$s$^{-1}$ |

The different experiments are sensitive to different parts of the energy spectrum of solar neutrinos and putting all these results together seems to indicate that the solution to the problem is not astrophysical but must concern the neutrino properties. Moreover, non-standard astrophysical solutions are strongly constrained by helioseismology studies \cite{11,12}. Within the standard solar model approach, the theoretical predictions clearly lie far from the best-fit solution what leads us to conclude that new particle physics is the only way to account for the data.

The standard explanation for this deficit would be the oscillation of $\nu_e$ to another neutrino species either active or sterile. Different analyses have been performed to find the allowed mass differences and mixing angles in the two-flavour approximation \cite{13,15}. The last result from Refs. \cite{14,15} indicate that for oscillations into active neutrinos there are three possible solutions:

- vacuum (also called “just so”) oscillations with $\Delta m^2_{ee} = (0.5-8) \times 10^{-10}$ eV$^2$ and $\sin^2(2\theta) = 0.5-1$;
- non-adiabatic-matter-enhanced oscillations via the MSW mechanism \cite{16} with $\Delta m^2_{ee} = (0.4-1) \times 10^{-5}$ eV$^2$ and $\sin^2(2\theta) = (1-10) \times 10^{-3}$, and
- large mixing via the MSW mechanism with $\Delta m^2_{ee} = (0.3-3) \times 10^{-4}$ eV$^2$ and $\sin^2(2\theta) = 0.6-1$.

In Fig. 2 I show the allowed two-flavour regions obtained in an updated MSW global fit analysis of the solar neutrino data for the case of active neutrino conversions. The analysis uses the model from \cite{17} but with an arbitrary \textit{hep} (from the reaction $^3$He $+ p \rightarrow ^4$He $+ e^+ + \nu_e$) neutrino flux \cite{14}.

Fig. 2 shows the regions of just-so oscillation parameters obtained in a recent global fit of the data. It has been pointed out that the expected
seasonal effects in this scenario (due to the variation of the Earth-Sun distance) could be used to further constrain the parameters [18], and also to help discriminating it from the MSW transition.

For oscillations into an sterile neutrino there are differences partly due to the fact that now the survival probability depends both on the electron and neutron density in the Sun but mainly due to the lack of neutral current contribution to the Kamiokande experiment. This last effect requires a larger $\nu_e$ survival probability. As a result the vacuum oscillation solution is very marginal and the large mixing MSW solution is ruled out. The small mixing solution is still valid [14,19].

The large mixing solution for oscillations into sterile neutrinos is also in conflict with the constraints from big bang nucleosynthesis (BBN) [20]. The presence of additional weakly interacting light particles, such as a light sterile neutrino, is constrained by BBN since the $\nu_s$ would enter into equilibrium with the active neutrinos in the early Universe via neutrino oscillations. However the derivation of the BBN bounds may be subject to large systematical uncertainties. For example, it has been argued in [21] that present observations of primordial Helium and deuterium abundances can allow up to $N_\nu = 4.5$ neutrino species if the baryon to photon ratio is small. The presence of a relic lepton number asymmetry in the early universe may also relax this constraint [22].

2.2. Atmospheric Neutrinos

Atmospheric showers are initiated when primary cosmic rays hit the Earth’s atmosphere. Secondary mesons produced in this collision, mostly pions and kaons, decay and give rise to electron and muon neutrino and anti-neutrinos fluxes [23]. There has been a long-standing anomaly between the predicted and observed $\nu_\mu / \nu_e$ ratio of the atmospheric neutrino fluxes [4]. Although the absolute individual $\nu_\mu$ or $\nu_e$ fluxes are only known to within 30% accuracy, different authors agree that the $\nu_\mu / \nu_e$ ratio is accurate up to a 5% precision. In this resides our confidence on the atmospheric neutrino anomaly (ANA), now strengthened by the high statistics sample collected at the Super-Kamiokande experiment [5]. The most important feature of the atmospheric neutrino 535-day data sample reported by the SK collaboration at Neutrino 98 [5] is that it exhibits a zenith-angle-dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino fluxes. This experiment has marked a turning point in the significance of the ANA.

Figure 3. Theoretically expected zenith angle distributions for SK electron and muon-like sub-GeV and multi-GeV events in the SM (no-oscillation) and for the best-fit points of the various oscillation channels, from Ref. [26]. The data points correspond to the 535 days of data taken from Superkamiokande [5].
the theoretically expected distribution in the absence of oscillation, while the predictions for the best-fit points of the various oscillation channels is indicated as follows: for $\nu_\mu \rightarrow \nu_e$ (solid line), $\nu_\mu \rightarrow \nu_\tau$ (dashed line) and $\nu_\mu \rightarrow \nu_s$ (dotted line). The error displayed in the experimental points is only statistical.

In the theoretical analysis it has been used the latest improved calculations of the atmospheric neutrino fluxes as a function of zenith angle, including the muon polarization effect and took into account a variable neutrino production point \cite{24}. Clearly the data are not reproduced by the no-oscillation hypothesis, adding substantially to our confidence that the atmospheric neutrino anomaly is real.

The most likely solution of the ANA involves neutrino oscillations \cite{25}. In principle we can invoke various neutrino oscillation channels, involving the conversion of $\nu_\mu$ into either $\nu_e$ or $\nu_\tau$ (active-active transitions) or the oscillation of $\nu_\mu$ into a sterile neutrino $\nu_s$ (active-sterile transitions) \cite{26,27}. In Fig. 4 I show the allowed neutrino oscillation parameters obtained in a recent global fit of the sub-GeV and multi-GeV (vertex-contained) atmospheric neutrino data \cite{26} including the recent data reported at Neutrino 98, as well as all other experiments combined at 90 (thick solid line) and 99 % CL (thin solid line) for each oscillation channel considered. The two lower panels in Fig. 4 differ in the sign of the $\Delta m^2$ which was assumed in the analysis of the matter effects in the Earth for the $\nu_\mu \rightarrow \nu_s$ oscillations. It was found that $\nu_\mu \rightarrow \nu_\tau$ oscillations give a slightly better fit than $\nu_\mu \rightarrow \nu_s$ oscillations.

At present the atmospheric neutrino data cannot distinguish between the $\nu_\mu \rightarrow \nu_\nu$ and $\nu_\mu \rightarrow \nu_s$ channels. Notice that in all channels where matter effects play a role the range of acceptable $\Delta m^2$ is shifted towards larger values, when compared with the $\nu_\mu \rightarrow \nu_\tau$ case. This follows from looking at the relation between mixing in vacuo and in matter. In fact, away from the resonance region, independently of the sign of the matter potential, there is a suppression of the mixing inside the Earth. As a result, there is a lower cut in the allowed $\Delta m^2$ value, and it lies higher than what is obtained in the data fit for the $\nu_\mu \rightarrow \nu_\tau$ channel.

Figure 4. Allowed atmospheric oscillation parameters for all experiments including the SK data reported at Neutrino 98, combined at 90 (thick solid line) and 99 % CL (thin solid line) for all possible oscillation channels, from Ref. \cite{26}. The sensitivity of the present accelerator and reactor experiments as well as the expectations of upcoming long-baseline experiments is also displayed.
I also display in Fig. 4 the sensitivity of present accelerator and reactor experiments, as well as that expected at future long-baseline (LBL) experiments in each channel. The first point to note is that the Chooz reactor [28] data already excludes the region indicated for the $\nu_\mu \rightarrow \nu_e$ channel when all experiments are combined at 90% CL. From the upper-left panel in Fig. 4 one sees that the regions of $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters obtained from the atmospheric neutrino data analysis cannot be fully tested by the LBL experiments, as presently designed. One might expect that, due to the upward shift of the $\Delta m^2$ indicated by the fit for the sterile case (due to the effects of matter in the Earth) it would be possible to completely cover the corresponding region of oscillation parameters. Although this is the case for the MINOS disappearance test, in general most of the LBL experiments can not completely probe the region of oscillation parameters allowed by the $\nu_\mu \rightarrow \nu_\tau$ atmospheric neutrino analysis. This is so irrespective of the sign of $\Delta m^2$ assumed. For a discussion of the various potential tests that can be performed at the future LBL experiments in order to unravel the presence of oscillations into sterile channels see Ref. 20.

2.3. LSND

Los Alamos Meson Physics Facility (LSND) has searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with $\bar{\nu}_\mu$ from $\mu^+$ decay at rest. The $\bar{\nu}_e$'s are detected in the quasi elastic process $\bar{\nu}_e p \rightarrow e^+ n$ in correlation with a monochromatic photon of 2.2 MeV arising from the neutron capture reaction $np \rightarrow d\gamma$. In Ref. 21 they report a total of 22 events with $e^+$ energy between 36 and 60 MeV while $4.6 \pm 0.6$ background events are expected. They fit the full $e^+$ event sample in the energy range $20 < E_e < 60$ MeV by a $\chi^2$ method and the result yields $64.3^{+18.5}_{-16.7}$ beam-related events. Subtracting the estimated neutrino background with a correlated gamma of $12.5 \pm 2.9$ events results into an excess of $51.8^{+18.7}_{-16.9} \pm 8.0$ events. The interpretation of this anomaly in terms of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations leads to an oscillation probability of $(0.31^{+0.11}_{-0.10} \pm 0.05)\%$. Using a likelihood method they obtain a consistent result of $(0.27^{+0.12}_{-0.12} \pm 0.04)\%$. In the two-family formalism this result leads to the oscillation parameters compared with the 90 % exclusion regions from other experiments.

2.4. Dark Matter

There is increasing evidence that more than 90% of the mass in the Universe is dark and non-baryonic. Neutrinos, if massive, constitute a source for dark matter. Stable neutrinos can fill the Universe of hot dark matter if their masses add up to a maximum of about 30 eV. However, scenarios with only hot dark matter run into trouble in the explanation of the formation of structures on small scales of the Universe. The research on the nature of the cosmological dark matter and the origin of galaxies and large scale structure in the Universe within the standard theoretical framework of gravitational collapse of fluctuations as the origin of structure in the expanding universe has undergone tremendous progress recently. Indeed the observations of cosmic background temperature anisotropies
on large scales performed by the COBE satellite combined with cluster-cluster correlation data e.g. from IRAS cannot be reconciled with the simplest cold dark matter (CDM) model.

Currently, the best scenario for a zero cosmological constant to explain the data considers a mixture of cold plus hot dark matter. This translates into an upper limit on neutrino masses:

\[ \sum m_{\nu_i} < \text{few eV} \]  

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This mass scale is similar to that indicated by the hints reported by the LSND experiment.

Very recent data on Type-I supernovae at high redshifts has provided evidence at more than 99 % CL for an accelerating expansion of the universe. They measure the light curve of the supernovae which gives the absolute luminosity. In this way they are able to determine the distance as a function of the redshift, and from there to measure the deceleration parameter \( q_0 = \Omega_M/2 - \Omega_\Lambda \). They find \( q_0 < 0 \). \( q0 \) gives a measurement of the different contributions to the energy density in the universe coming from matter and from the presence of a cosmological constant.

In a flat universe both contributions must verify \( \Omega_M + \Omega_\Lambda = 1 \). In other words, the data from supernovae searches indicate a non-zero cosmological constant, or equivalently, \( \Omega_M < 1 \). Actually the results indicate, for a flat universe, \( \Omega_M < 0.5 \) at 99 % CL.

Should these results be confirmed the amount of dark matter of the universe would be considerably reduced and in consequence the corresponding limit on the stable neutrino mass will become tighter. Future sky maps of the cosmic microwave background radiation (CMBR) with high precision at the upcoming MAP and PLANCK missions should bring more light into the nature of the dark matter and the possible role of neutrinos.

3. Reconciling the neutrino puzzles

Naive two-family counting shows that it is very difficult to fit all experimental information even in the three neutrino scenario, even without invoking the LSND data. One has to choose between throwing away part of the data and considering a larger scheme.

The solar neutrino deficit could be due to \( \nu_e \rightarrow \nu_\mu \) oscillations and the atmospheric neutrino deficit to \( \nu_\mu \rightarrow \nu_\tau \) oscillations with the appropriate mass differences, for example with a mass hierarchy \( m_{\nu_\tau} \gg m_{\nu_\mu}, m_{\nu_e} \). However, fitting this together with the present laboratory limits leaves no room for hot dark. The only possible way out is to require that all three neutrinos are almost degenerate. This requires a certain degree of fine-tuning in order to explain the neutrinoless double beta decay data. Notice that this scenario is also inconsistent with the oscillation parameters observed by LSND.

One could have \( \nu_\mu \rightarrow \nu_\tau \) oscillations for the atmospheric neutrino deficit with almost degenerate \( \nu_\mu \) and \( \nu_\tau \) with masses \( m_{\nu_\mu} = m_{\nu_\tau} \approx \text{few eV} \) and \( m_{\nu_e} \approx 0 \), but leaving out the explanation for the solar neutrino deficit. Or \( m_{\nu_\mu} = m_{\nu_e} \approx 0 \) and \( m_{\nu_\tau} \approx \text{few eV} \) to explain the atmospheric data but leaving unexplained both solar neutrino deficit and dark matter.

Also, it is possible to explain the solar neutrino deficit with \( \nu_e \rightarrow \nu_\tau(\mu) \) with almost degenerate \( \nu_e \) and \( \nu_\tau(\mu) \) with masses \( m_{\nu_e} = m_{\nu_\tau(\mu)} \approx \text{few eV} \) and \( m_{\nu_\mu} \approx 0 \), but leaving the atmospheric neutrino deficit unexplained. Also \( m_{\nu_e} = m_{\nu_\tau} \approx 0 \) and \( m_{\nu_\mu} \approx \text{few eV} \) would explain the LSND data if confirmed but leaves both atmospheric and dark matter without explanation.

The “minimal” scheme to explain all data without fine-tuning seems to be a four-neutrino framework \( (\nu_e, \nu_\mu, \nu_\tau, \nu_s) \) where \( \nu_s \) is a sterile neutrino.

3.1. Four-Neutrino Models

The simplest way to open the possibility of incorporating the LSND scale to the solar and atmospheric neutrino scales is to invoke a sterile neutrino, i.e. one whose interaction with standard model particles is much weaker than the SM weak interaction so it does not affect the invisible Z decay width, precisely measured at LEP. The sterile neutrino must also be light enough in order to participate in the oscillations involving the three active neutrinos.

After imposing the present constrains from the negative searches at accelerator and reactor
Scenarios I and II are described using the following matrix:

\[
\begin{array}{ccc}
\Delta m_{\text{atm}}^2 & \nu_{\mu},\nu_{X} & \Delta m_{\text{solar}}^2 \\
\Delta m_{\text{LSND}}^2 & \nu_{e},\nu_{X'} & \Delta m_{\text{atm}}^2 \\
\Delta m_{\text{solar}}^2 & \nu_{e},\nu_{X'} & \Delta m_{\text{atm}}^2 \\
\end{array}
\]

These two possible mass patterns as described in Fig. 6 which I will call scenario I and II. In scenario I there are two lighter neutrinos at the solar neutrino mass scale and two maximally mixed almost degenerate eV-mass neutrinos split by the atmospheric neutrino scale. In scenario II the two lighter neutrinos are maximally mixed and split by the atmospheric neutrino scale while the two heavier neutrinos are almost degenerate separated by the solar neutrino mass difference. In both scenarios solar neutrino data together with reactor neutrino constrains, imply that the electron neutrino must be maximally projected over one of the states belonging to the pair split by the solar neutrino scale: the lighter (heavier) pair for scenario I (II). On the other hand, atmospheric neutrino data together with the bounds from accelerator neutrino oscillation experiments imply that the muon neutrino must be maximally projected over the pair split by the atmospheric neutrino mass difference: the heavier (lighter) pair for scenario I (II).

In both scenarios there are two possible assignments for the sterile and tau neutrinos which I denote by .a and .b depending on whether the tau neutrino is maximally projected over the pair responsible for the atmospheric neutrino oscillations and the sterile neutrino is responsible for the solar neutrino deficit ($\nu_X = \nu_\tau$ and $\nu_{X'} = \nu_e$) or viceversa ($\nu_X = \nu_e$ and $\nu_{X'} = \nu_\tau$). These four possibilities offer different signatures at future experiments:

- In scenario II the electron neutrino must be mainly composed of one of the heavier states with a mass characteristic of the LSND mass difference and the dark matter $m_1 = m_{DM}/2 = \sqrt{\Delta m_{\text{LSND}}^2} \sim 0.1$ eV and may be tested at future neutrinoless double-$\beta$ decay and tritium $\beta$ decay experiments.

- Scenarios I.a and II.a give a slightly better fit to the atmospheric neutrino anomaly. Future long baseline experiments can be sensitive to this oscillation and the most sensitive test would be a $\tau$ appearance experiment.

- Scenarios I.b and II.b where the atmospheric $\nu_\mu$ deficit is due to the oscillation into an sterile neutrino imply a higher value of $\Delta m_{\text{atm}}^2$ as can be seen in Fig. 4 due to the effect of propagation through the Earth which suppresses the lower mass region. As a consequence this scenario can be easier to test at future long baseline experiments. However only a disappearance-type experiment is possible and, in general these tests can achieve lower sensitivity.

- For solar neutrinos the three regions discussed in subsection 2.1 are valid for scenarios I.a and II.a when the solar data is explained in terms of $\nu_e \rightarrow \nu_{\mu}$. For scenarios I.b and II.b where $\nu_e \rightarrow \nu_s$ are invoked to account for the solar neutrino deficit, there are differences mainly due to the lack of neutral current contribution to the Kamiokande experiment. This last effect requires a larger $\nu_e$ survival probability. As a result the vacuum oscillation solution is very marginal and the large mixing MSW solution is ruled out.

- The neutral-to-charged current ratio is a very important observable in neutrino os-
cillation phenomenology, which is especially sensitive to the existence of singlet neutrinos. This test can be carried out both at future solar and atmospheric neutrino experiments as well as long baseline experiments. At present one may study the ratios of $\pi^0$-events and the events induced mainly by the charged currents [33]. Superkamiokande has reported the result [5]

$$\frac{\langle \pi^0/e \rangle_{\text{data}}}{\langle \pi^0/e \rangle_{\text{MC}}} = 0.93 \pm 0.07 \pm 0.19$$

The expected values are 1. (0.75) for scenarios I.a and II.a (I.b and II.b). The result above is consistent with both scenarios with a slight preference for the former.

- In scenarios I.b and II.b the sterile neutrino is largely mixed with one active neutrino. This gives a larger contribution to the effective degrees of freedom at the time of BBN. Should the BBN constrains become more precise, these scenarios may be ruled out.

4. Conclusions

The impressive re-confirmation of an angle-dependent atmospheric neutrino deficit by Superkamiokande leaves little room for doubt that the atmospheric neutrino anomaly is an strong evidence for neutrino masses and mixings. Likewise, it has become more and more difficult to avoid neutrino oscillations as an explanation for the solar neutrino puzzle. Also the LSND evidence for $\bar{\nu}_e - \bar{\nu}_\mu$-oscillations still remains a viable hypothesis although more restricted by the exclusion limit of the KARMEN experiment. These three results can be interpreted in terms of neutrino oscillations but with the need of three different mass scales. Thus if the LSND result stands the test of time, this would be a puzzling indication for the existence of a light sterile neutrino.

The two scenarios to reconcile these observations invoke either $\nu_e \rightarrow \nu_\tau$ oscillations to explain the solar data, with $\nu_\mu \rightarrow \nu_\tau$ oscillations accounting for the atmospheric deficit, or vice-versa. They have distinct implications at future tritium beta decay and neutrino-less double beta decay experiments as well as solar, atmospheric and long baseline neutrino experiments. In particular the neutral-to-charged current ratio is an important observable to discriminate among the different scenarios as it is sensitive to the existence of singlet neutrinos. This test can be carried out both at future solar and atmospheric neutrino experiments as well as long baseline experiments.

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