NEUTRINO MASS TEXTURES AND THE NATURE OF NEW PHYSICS IMPLIED BY PRESENT NEUTRINO DATA

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If all the indications for neutrino oscillations observed in the solar, atmospheric neutrino data as well as in the LSND experiment are borne out by the ongoing and future experiments, then they severely constrain the neutrino mass texture. In particular, the need for an extra ultra-light sterile neutrino species is hard to avoid. Such an extra neutrino has profound implication not only for physics beyond the standard model but even perhaps for physics beyond conventional grand unification. We discuss a scenario involving a parallel (or shadow) universe that interacts with the familiar universe only via the gravitational interactions where the ultra-lightness of the sterile neutrino follows from the same physics that explains the near masslessness of the familiar neutrinos.

1 Introduction

There are several different observations involving neutrinos which receive a plausible and satisfactory explanation if the neutrinos are massive. First is the well-known solar neutrino deficit, observed by four different experiments. Second is the deficit of muon neutrinos relative to electron neutrinos produced in the atmosphere, as measured by three experiments. Third is the reported evidence for $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation from the Los Alamos Liquid Scintillation Neutrino Detector (LSND) experiment. Finally, there is the likely need for a neutrino component of the dark matter of the universe to understand the structure and density on all distance scales. Since the highly successful standard model of particle physics predicts zero mass for all the neutrinos, confirmation of any one of the above observations by ongoing and future experiments will already be a major step towards decoding the nature of new physics beyond the standard model. If however all the above findings are substantiated in future, one can reasonably expect the nature of this new physics to fall into only very few categories. In this talk, I will assume the validity of all the above findings (although it is clear that they must be considered tentative until further confirmation by ongoing and future experiments) and argue first that it severely restricts the neutrino mass texture and in particular requires the existence of a new ultra-light sterile neutrino. I will then outline the two see-saw formulae for understanding the small neutrino masses, and discuss their implementation.

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in SO(10) models. I will then argue that the simplest scenario which explains
the lightness of the sterile neutrino in a natural manner is one that involves a
shadow universe which has identical particle and force content as the familiar
universe but with the weak scale being somewhat higher.

1.1 Solar Neutrino Deficit

For massive neutrinos which can oscillate from one species to another, the
solar electron neutrino observations can be understood if the neutrino mass
differences and mixing angles fall into one of the following ranges, where the
Mikheyev-Smirnov-Wolfenstein (MSW) mechanism is included:

\[ \Delta m^2_{ee} \sim 5 \times 10^{-6} \ - 10^{-5} \text{eV}^2, \ \sin^2 2\theta_{ei} \sim 7 \times 10^{-3}, \]
\[ \Delta m^2_{ei} \sim 9 \times 10^{-6} \text{eV}^2, \ \sin^2 2\theta_{ei} \sim 0.6, \]

(1)

If the solar neutrinos oscillate into sterile neutrinos, the MSW effect is different
from the $\nu_e \to \nu_\mu$ case and the large angle solution is no more allowed. The
above results are based on the approximation that only two of the neutrino
species are involved in the oscillation.

1.2 Atmospheric Neutrino Deficit

The second set of experiments indicating non-zero neutrino masses and mixings
has to do with atmospheric $\nu_\mu$’s and $\nu_e$’s arising from the decays of $\pi$’s and $K$’s
and the subsequent decays of secondary muons produced in the final states of
the $\pi$ and $K$ decays. In the underground experiments the $\nu_\mu$ and $\bar{\nu}_\mu$ produce
muons and the $\nu_e$ and $\bar{\nu}_e$ lead to $e^\pm$. Observations of $\mu^\pm$ and $e^\pm$ indicate a far
lower value for $\nu_\mu$ and $\bar{\nu}_\mu$ than suggested by naïve counting arguments which
imply that $N(\nu_\mu + \bar{\nu}_\mu) = 2N(\nu_e + \bar{\nu}_e)$. If one assumes that the oscillation
of $\nu_\mu$ to $\nu_\tau$ provides an explanation of these results, then to fits to both the
sub-GeV and multi-GeV data require that

\[ \Delta m^2_{\mu\tau} \approx 0.025 \text{ to } 0.005 \text{ eV}^2, \ \sin^2 2\theta_{\mu\tau} \approx 0.6 \text{ to } 1. \]

(2)

A recent reanalysis of the data seems to imply that the data allows an upper
limit on the $\Delta m^2$ upto .25 eV$^2$ at 90% confidence level.

1.3 Results from the LSND experiment

Recently, the LSND collaboration has published the results of their search for
$\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation using the liquid scintillation detector at Los Alamos. Com-
bining their results which indicate a positive result with the negative results
by the E776 group and the Bugey reactor data, one can conclude that a mass difference squared between the $\nu_e$ and the $\nu_\mu$ lies between

$$0.27 \text{ eV}^2 \leq \Delta m^2 \leq 2.3 \text{ eV}^2$$

with points at 6 and 10 eV$^2$ also perhaps allowed.

1.4 Hot Dark Matter

There is increasing evidence that more than 90% of the mass in the universe must be detectable so far only by its gravitational effects. This dark matter is likely to be a mix of $\sim 20\%$ of particles which were relativistic at the time of freeze-out from equilibrium in the early universe (hot dark matter) and $\sim 70\%$ of particles which were non-relativistic (cold dark matter). Such a mixture gives the best fit of any available model to the structure and density of the universe on all distance scales, such as the anisotropy of the microwave background, galaxy-galaxy angular correlations, velocity fields on large and small scales, correlations of galaxy clusters, etc. A very plausible candidate for hot dark matter is one or more species of neutrinos with total mass of $m_{\nu_H} = 93h^2 F_H \Omega = 4.8$ eV, if $h = 0.5$ (the Hubble constant in units of 100 km·s$^{-1}$·Mpc$^{-1}$), $F_H = 0.3$ (the fraction of dark matter which is hot), and $\Omega = 1$ (the ratio of density of the universe to closure density).

It is usually assumed that the $\nu_\tau$ would supply the hot dark matter. However, if the atmospheric $\nu_\mu$ deficit is due to $\nu_\mu \rightarrow \nu_\tau$, the $\nu_\tau$ alone cannot be the hot dark matter, since the $\nu_\mu$ and $\nu_\tau$ need to be closer to each other in mass. It is interesting that instead of a single $\sim 4.8$ eV neutrino, sharing that $\sim 4.8$ eV between two or among three neutrino species provides a better fit to the universe structure and particularly a better understanding of the variation of matter density with distance scale.

It is worth noting that an equally popular picture adopts the hypothesis that there is a large cosmological constant ($\Omega_\Lambda = .8$ or so) in a low density baryon plus CDM universe to make up $\Omega = 1$. This has been inspired by reported large values ($h_0 = .7 - .8$ or so) of the Hubble parameter from several observation which have hard time fitting the age of the universe (e.g. from globular clusters) with $\Omega = 1$ without a cosmological constant. There are however other observations that give a lower value for $h_0$ ($h_0 \simeq .5$). The final verdict on the dark matter picture of the universe will therefore have to wait. It is nevertheless heartening that there is a compelling case for a neutrino mass in the eV range from structure formation in the universe.

In understanding the detailed implications of these data for physics beyond the standard model, one must also take into account other constraints
on neutrinos, from nucleosynthesis, the Heidelberg-Moscow $\beta\beta_0\nu$ experiment searching for the Majorana mass of the neutrino using enriched $^{76}\text{Ge}$ and the synthesis of heavy elements supposedly by the rapid neutron capture process (the so-called $r$-process) around supernovae.

1.5 Other constraints:

(i) While the $Z^0$ width limits the number of weakly interacting neutrino species to three, the nucleosynthesis limit of about 3.3 on the number of light neutrinos is more useful here, since it is independent of the neutrino interactions. Invoking a fourth neutrino, $\nu_s$, which is sterile, meaning it does not have the usual weak interaction, must be done with parameters such that it will not lead to overproduction of light elements in the early universe. For example, the atmospheric $\nu_\mu$ problem cannot be explained by $\nu_\mu \rightarrow \nu_s$, since $\sin^2 2\theta_{\mu s} \approx 0.5$ is too large for the $\Delta m^2_{\mu s}$ involved, and that $\nu_s$ would have been brought into equilibrium in the early universe. On the other hand, the solar $\nu_e$ problem can be explained by $\nu_e \rightarrow \nu_s$ for either the small-angle MSW or the vacuum oscillation solutions, but not for the less favored large-angle MSW solution.

(ii) The Heidelberg-Moscow $^{76}\text{Ge}$ experiment has been conducting a high precision search for neutrinoless double beta decay for the past several years and have at present set the most stringent upper limits on the effective Majorana mass of the neutrino: $<m_\nu> \leq 0.56$ eV.

(iii) It has been pointed out that in minimal model with three massive neutrinos, supernova r-processes provide a very stringent constraint on the neutrino mixings for eV mass range or higher. The origin of this constraint can be understood as follows. Inside the supernova, the MSW phenomenon enhances the conversion of the muon neutrinos (which have higher energy) to electron neutrinos if the mass difference square $\Delta m^2 \geq 4 (\text{eV})^2$ while leaving the $\bar{\nu}_\mu$'s unaffected. The newly born high energy $\nu_e$'s deplete the neutron content of the supernova environment via the reaction $\nu_e + n \rightarrow e^- + p$. This reduction of the neutron content slows down the r-process making it difficult to understand the heavy element abundance of the present universe. This result crucially hinges on the assumption that $m_{\nu_\mu} \geq m_{\nu_e}$ and that there are neutrinos that $\nu_\mu$ mixes with. In fact in the presence of sterile neutrinos, its mixing with $\nu_\mu$ can lead to MSW enhancement of $\nu_\mu$ to $\nu_s$ conversion deeper in the supernova providing a way out of this constraint.

2 Neutrino mass textures consistent with data

In discussing the neutrino mass textures in this section, we will assume that all the neutrinos are Majorana particles, since it is easier to understand the
smallness of Majorana masses of neutrinos within the framework of grand unified theories. Before going to a detailed discussion of the allowed mass matrices, let us note two generic requirements for the allowed mass matrices dictated by the data: (i) at least two neutrinos must be degenerate in mass; and (ii) there is a very compelling case for the existence of a sterile neutrino in the present data.

2.1 Are neutrinos degenerate?

If only two of the above hints (either solar and atmospheric data or solar and HDM) are taken seriously, then one can maintain a hierarchical picture for neutrino masses i.e. $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$. Such a pattern emerges very naturally in one class of the see-saw models (see below). However, if we take any three of the above four hints for neutrino masses, then we must have at least two neutrinos degenerate. To see the case for a sterile neutrino, let us first note that it is not easy to write down a neutrino mass matrix within the three generation picture that can accommodate all the above observations as well as constraints. The main obstacle comes from the conflict between the LSND data and the MSW resolution of the solar neutrino data. The first requires that $\Delta m^2_{\nu_e-\nu_\mu}$ is in the eV range which is much larger than the mass difference required to explain the solar neutrino data. If we ignore the LSND data, the solar, atmospheric data and the HDM neutrino can be accommodated in a three neutrino scenario by assuming that all three neutrinos are degenerate in mass. One very marginal possibility has been advocated recently using a variant of this, to accommodate the LSND results in this picture provided the LSND $\Delta m^2$ is chosen to be around $0.3 \text{ eV}^2$. First point to note is that since solar neutrino puzzle requires that $\Delta m^2_{\nu_e-\nu_\mu} \approx 10^{-5} \text{ eV}^2$, to understand the LSND results in this scenario, one must use the complete three neutrino oscillation keeping all mixing angles. This requires first that $\nu_e-\nu_\tau$ mixing angle is not too small. Secondly, we must have $\Delta^2_{\mu-\tau} \approx 3 \text{ eV}^2$. Thus the oscillation frequency is determined by $\nu_e-\nu_\tau$ mass difference. The main problem for this scenario comes from the atmospheric neutrino data, since the original analysis of the Kamiokande sub-GeV and the multi-GeV data by the Kamiokande group excludes $\Delta m^2 \geq 0.1 \text{ eV}^2$ at 90% confidence level (c.l.). As mentioned earlier, a subsequent analysis extends this range further excluding only the $\Delta m^2 \geq 0.25 \text{ eV}^2$ at 90% confidence level while allowing it at 95% c.l. level. While at its face a value of $m_{\nu_e} \approx 1.6 \text{ eV}$ may appear to be in conflict with the neutrinoless double beta decay limit, one can hide under the uncertainties of nuclear matrix element calculations which typically could be as much as a factor of 2-3. As the precision in $\beta\beta_{0v}$ search improves further
(say to the level of 0.1 eV), nuclear matrix element uncertainties cannot come to the rescue and this mass texture will then be ruled out. One can write the neutrino Majorana mass matrix for this case as follows:

\[
M = \begin{pmatrix}
    m + \delta_1 s_1^2 & -\delta_1 c_1 c_2 s_1 & -\delta_1 c_1 s_1 s_2 \\
    -\delta_1 c_1 c_2 s_1 & m + \delta_1 c_1^2 c_2^2 + \delta_2 s_2^2 & \delta_1 c_1^2 c_2 s_2 - \delta_2 c_2 s_2 \\
    -\delta_1 c_1 s_1 s_2 & \delta_1 c_1^2 c_2 s_2 - \delta_2 c_2 s_2 & m + \delta_1 c_1^2 s_2^2 + \delta_2 c_2^2
\end{pmatrix},
\]

(4)

where \( c_i = \cos \theta_i \) and \( s_i = \sin \theta_i \), \( m = 1.6 \text{ eV} \); \( \delta_1 \simeq 1.5 \times 10^{-5} \text{ eV} \); \( \delta_2 \simeq 0.1 \text{ eV} \); \( s_1 \simeq 0.05 \); and \( s_2 \simeq 0.4 \) for the small-angle MSW solution.

2.2 The need for a sterile neutrino

We thus see that if the above scenario is ruled out, for instance by the tightening of the double beta decay limit on the Majorana mass of \( \nu_e \) or by the atmospheric neutrino data, then the only way to understand all neutrino results will be to assume the existence of an additional neutrino species which in view of the LEP data must not couple (or couple extremely weakly) to the Z-boson. We will call this the sterile neutrino. The picture then would be as follows: the solar neutrino puzzle is explained by the \( \nu_e - \nu_s \) oscillation; atmospheric neutrino data would be explained by the \( \nu_\mu - \nu_\tau \) oscillation. The LSND data would set the overall scale for the masses of \( \nu_\mu \) and \( \nu_\tau \) (which are nearly degenerate) and if this scale is around 2 to 3 eV as is allowed by the data, then the \( \nu_\mu, \tau \) would constitute the hot dark matter of the universe. The mass matrix in this case would be in the basis \( (\nu_s, \nu_e, \nu_\mu, \nu_\tau) \),

\[
M = \begin{pmatrix}
\mu_1 & \mu_3 & \epsilon_{11} & \epsilon_{12} \\
\mu_3 & \mu_2 & \epsilon_{21} & \epsilon_{22} \\
\epsilon_{11} & \epsilon_{21} & m & \delta/2 \\
\epsilon_{12} & \epsilon_{22} & \delta/2 & m + \delta
\end{pmatrix},
\]

(5)

For simplicity, we set the \( \epsilon_{12} = \epsilon_{22} = 0 \) and \( \mu_2 \ll \mu_1 \simeq 10^{-3} \text{ eV} \). The \( \epsilon_{11} \) term is responsible for the \( \nu_\mu - \nu_\mu \) oscillation that can explain the LSND data. The apparent problem for such a scenario comes from the supernova r-process nucleosynthesis. But it has been argued that in such a scenario, the \( \nu_\mu \) can oscillate into the \( \nu_s \) at a smaller protoneutron star radius before it reaches the radius where \( \nu_\mu \) to \( \nu_\mu \) MSW transition occurs. This may enable one to evade the r-process bound for \( \Delta m^2_{\nu_\mu} \geq 4 \text{ eV}^2 \). Clearly the crucial test of the sterile neutrino scenario will come when SNO collaboration obtains their results for neutral current scattering of solar neutrinos. One would expect that \( \Phi_{\text{CC}} = \Phi_{\text{NC}} \) if the \( \nu_e \) oscillation to \( \nu_s \) is responsible for the solar neutrino deficit. There should be no signal in \( \beta_\beta_{0w} \) search. Precision measurement
of the energy distribution in charged current scattering of solar neutrinos at Super-Kamiokande can also shed light on this issue.

Before proceeding to the discussion of the theoretical implications of the mass textures outlined above, we want to note that if the atmospheric neutrino data is excluded but LSND, HDM and solar neutrino constraints are kept, a theoretical explanation for them can be found also with an inverted mass texture for neutrinos where the $m_{\nu_e} \simeq m_{\nu_\tau} \simeq 2.4 \, eV \gg m_{\nu_\mu}$ and which does not invoke the sterile neutrino. This texture is consistent with the supernova r-process constraints and uses the $\nu_e \rightarrow \nu_\tau$ large angle MSW solution to explain the solar neutrino data. This could therefore be tested once Super Kamiokande results for the neutrino energy spectrum as well as the data on day-night variation is in.

### 3 Implications for higher unification and two types of see-saw mechanism

In this section we address the question of what implications the small nonzero neutrino masses and in particular any of the scenarios discussed above have for the nature for the nature of new physics beyond the standard model. To start with let us remind the reader that in the standard model the presence of an exact global B-L symmetry combined with the absence of the right handed neutrino leads to zero mass for all neutrinos. The simplest way to generate a nonzero neutrino mass is therefore to add three right handed neutrinos $N_i$, one per generation. It is easy to see that as soon as the $N_i$ are included, the maximal anomaly-free gaugeable symmetry becomes $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ which can eventually lead to an $SO(10)$ grand unification of fermions. As has been shown during the past decade and half, this class of models provide the most natural framework for describing the neutrino masses. What happens in these models is that as the $SU(2)_R \times U(1)_{B-L}$ gauge group breaks down to $U(1)_{Y}$, not only the right-handed gauge bosons but also the right handed neutrinos of all three generations acquire a mass $f v_R$ proportional to the $B - L$ breaking scale $v_R \gg v_W$, where $v_W$ is the electroweak symmetry breaking scale of the standard model. At this stage, the left handed neutrinos are massless. At the scale $v_W$, the Dirac mass for the neutrino that connects the left and the right handed neutrino is generated with a value given by $h v_W$ which is expected to be of the order of the masses of the charged fermions $m_f$ which also arise at that scale. This leads to the see-saw matrix for the neutrinos

$$M = \begin{pmatrix} 0 & m_f \\ m_f & M_N \end{pmatrix}$$
The diagonalization matrix leads to the generic formula for neutrino masses

\[ m_{\nu_i} \approx \frac{(m_f)^2}{M_{N_i}} \]  

This formula has two interesting implications: (i) the first is that the neutrinos, which are now necessarily Majorana fermions have masses which are suppressed compared to the masses of the charged fermions of the corresponding generation and (ii) the neutrino masses show a generationwise hierarchical pattern linked to the square of the masses of the charged fermions of the corresponding generation (i.e. \( m_{\nu_e} \ll m_{\nu_{\mu}} \ll m_{\nu_\tau} \)). We will call this the type I see-saw formula.

It was pointed out in \(^\text{[21]}\) that when the spontaneous symmetry breaking of the left-right model (or its SO(10) grand unified version) is carefully analyzed, one actually gets a modified neutrino mass matrix given by

\[
\begin{pmatrix}
\frac{\lambda v_W^2}{v_R} & m_f \\
m_f & M_N
\end{pmatrix}
\]  

Diagonalization of the above mass matrix leads to what I call the type II see-saw formula for the neutrino masses:

\[ m_{\nu_i} \approx \frac{\lambda v_W^2}{v_R} - \frac{m_f^2}{M_{N_i}} \]  

Note that the first term in the above formula is practically generation independent. Therefore, the neutrino mass pattern in this case is not hierarchical and could lead to a nearly degenerate spectrum as has been advocated in the previous section.

There are conditions under which the type II see-saw formula reduces to a type I see-saw formula: for instance when the discrete parity symmetry of the left-right or SO(10) models is broken at a scale higher than the \( SU(2)_R \times U(1)_{B-L} \) gauge symmetry, then the first term in the type II see-saw formula is replaced by \( \lambda v_W v_R^2 / M_P^2 \) (\( M_P \) being the scale of discrete parity breaking), which can clearly be arranged to yield the hierarchical mass pattern. Another class of models where the type I see-saw can emerge are some supersymmetric models with restricted Higgs representations.

A very interesting point worth emphasizing here is that if we look at the typical masses needed to solve the solar as well as the atmospheric neutrino puzzles and use the see-saw formula to find the scale of \( B - L \) symmetry breaking, we find that \( v_R \approx 10^{12} - 10^{13} \text{ GeV} \). It may be more than a mere
coincidence that the B-L breaking scale of $v_R \sim 10^{13}$ GeV emerges naturally from constraints of $\sin^2 2\theta_W$ and $\alpha_s$ in non-supersymmetric SO(10) grandunified theories, as well as supersymmetric SO(10) theories. In the least it enhances the reason for an SO(10) scenario. It is however possible to construct TeV scale right handed neutrino scenarios where the suppression of the neutrino mass originates from the fact that the Dirac masses are radiatively induced. To summarize this section, it is reasonable to conclude that evidence for a small neutrino mass would indicate the existence of a local $B-L$ symmetry in nature and perhaps even a left-right symmetry, which will be a major new dimension to our understanding of particle physics. Secondly, the generic class of grand unified models where the see-saw mechanism (both type I and type II) is naturally implemented are based on the $SO(10)$ GUT group with the type I see-saw leading to a hierarchical pattern for neutrino masses whereas the type II leads to a near degenerate pattern. In the next section, we explore whether definite predictions can be made for the neutrino masses and mixing angles in this class of models.

4 Predictions from minimal SO(10) grand unification models

If there are only three light neutrinos, it is both economical and elegant to work within simple $SO(10)$ grand unified models. While simple electroweak gauge theories without additional symmetries do not have the capability to predict fermion masses, the assumption of grand unification improves this record somewhat (e.g. the prediction of b-quark mass in $SU(5)$). In the minimal $SO(10)$ models, the neutrino Dirac mass and the up-quark mass matrices become equal since they both arise from the Yukawa couplings of the fermions (which belong to the $16$ dim representations) to the Higgs boson in the $10$-dim representation, thereby reducing the number of free parameters. This raises the possibility for a prediction of the neutrino masses in these models. The problem however is that the Majorana mass of the $N_i$ arises from the couplings of the fermions to the $126$ dimensional Higgs bosons. Since these couplings are arbitrary, in general no specific predictions can be made. It was however pointed out by Babu and this author that in the minimal $SO(10)$ models, the standard model doublets arise from an admixture of the $SU(2)_L$ doublets in $10$ and $126$ dimensional Higgs bosons. Therefore, the $126$ Yukawa couplings (as well as those to $10$) get predicted in terms of the quark, lepton masses and their mixings. This model (which is a realization of the type I see-saw mechanism) therefore leads to numerical predictions for the neutrino masses and mixings. The reader is referred to the original papers for the detailed predictions for the non-supersymmetric as well as supersymmetric versions.
of the model. There are actually six solutions depending on the relative signs of the various quark masses. Here we simply want to note that there are predictions in both versions that can accommodate the small angle MSW solution to the solar neutrino puzzle but not the atmospheric nor the LSND nor the HDM neutrino.

There is another class of $SO(10)$ models\textsuperscript{29} where additional symmetries are imposed to fix the heavy Majorana mass matrix for the right handed neutrinos and different popular quark mass textures are used for the neutrino Dirac masses. They also implement the type I see-saw formula and give generic predictions that can accommodate only the small angle MSW solutions to the solar neutrino puzzle.

Finally a different class $SO(10)$ models were studied\textsuperscript{30} where the type II see-saw mechanism was implemented. Using an additional $S_4$-permutation symmetry on the fermions and the Higgs bosons, it was possible to obtain a realization of the degenerate neutrino mass mixing angle predictions that can solve both the solar as well as the atmospheric neutrino problem.

5 Beyond grand unification: Into the shadow universe

Once we admit the possibility of light sterile neutrinos, one needs to go beyond simple grand unified models to understand why the sterile neutrino is so light. The reason for this is that the sterile neutrino by definition is an $SU(2)_L \times U(1)_Y$ singlet and therefore is allowed to have an arbitrary mass unless there are some compelling new symmetries that keep it massless. Attempts have been made using additional $U(1)$’s and supersymmetry\textsuperscript{31} etc to achieve this goal. But it is perhaps fair to say that there are no compelling motivations for such symmetries. To circumvent such arguments, it was proposed in\textsuperscript{32} to make the conjecture that there is an exact duplication of the standard model in both the gauge as well as the fermion content i.e. an extra $G’_{\text{standard}}$ with $Q’, u’c’, d’c’, L’, e’c’$ etc. (this adds a new sector to the world of elementary particles, which will be called the shadow sector). It is then clear that we have three extra neutrinos which do not interact with the $Z$-boson. We further assume that the only interactions that connect the known and the shadow sector is the gravitational interaction.

Within this framework, it is easy to understand that the shadow neutrinos (which will be the sterile neutrinos) are massless in the renormalizable theory for exactly the same reason that the ordinary neutrinos are (i.e. the existence of a $B’ - L’$ symmetry in the shadow standard model sector). We may assume that there is a ”shadow” see-saw mechanism which operates exactly the same way to give tiny masses to the shadow neutrinos. The next question is how
do the shadow (or sterile) neutrinos acquire small masses and mix with the known neutrinos? Here we use the existing lore that all global symmetries are broken by Planck scale effects. It was already pointed out that one can write Planck scale induced operators such as $LH_u LH_u/M_P$, $LH_u L'H'_u/M_P$ and $L'H'_u L'H'_u/M_P$ which violate both $B - L$ as well as $B' - L'$ symmetries and after electroweak symmetry breaking in both the sectors lead to $\nu - \nu'$ mixing. If we now make the additional assumption that $v'_W \simeq 30 v_W$, the resulting $\nu_e - \nu'_e$ mass matrix gives a solution to the solar neutrino puzzle with small mixing angles. When this idea is combined with the postulate that there exists an $L_e + L_\mu - L_\tau$ symmetry (instead of the overall $B - L$ symmetry) that is broken by Planck scale effects, we come up with a neutrino mass matrix that explains all neutrino puzzles using the four neutrino mass texture noted in Ref.\textsuperscript{13}.

The next interesting feature of these models is that if the $m_{\nu_e} \simeq m_{\nu_\tau} \simeq 2$ eV or so, then the $m_{\nu'_\mu} \simeq m_{\nu'_\tau} \simeq 2$ keV. Thus $\nu'_\mu, \nu'_\tau$ can qualify as warm (or cool) dark matter of the universe, a possibility which does not appear to have been ruled out present cosmological observations. Such models have many interesting implications for cosmology\textsuperscript{34}, which we will not go into here.

6 Conclusions

The solar, atmospheric and LSND neutrino data, along with a need for some hot dark matter, if all are due to neutrino mass have two very profound implications: (i) at least two neutrinos must be degenerate in mass, a feature not shared by charged fermions and not expected in the minimal SO(10) type models; (ii) there is a very good possibility that there is need for a sterile neutrino. In this talk, I have considered the various implications of these conclusions for physics beyond the standard model, such as the simple $SO(10)$ scenarios and conclude that one needs to go beyond such simple models if all the present indications neutrino mass are correct. I then outline the recent suggestion of Z. Berezhiani and this author that a scenario with a shadow universe with identical gauge and fermion structure (but with an asymmetric weak scale) can explain all the neutrino puzzles without the need for any other ingredients.

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