The Sterile Neutrino: First Hint of 4th Generation Fermions?

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In this letter, we introduce the “flipped see-saw mechanism”, a new type of see-saw mechanism with 4th-generation neutrinos. This mechanism naturally explains the light sterile neutrino which is needed to account for all neutrino oscillation data. At the same time it predicts that another Majorona neutrino should exist with mass of the electro-weak scale. We comment on some implications of this scenario on the oblique parameters used to parameterize precision electroweak measurements as well as on future experiments.

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Over the past several years our understanding of neutrino physics has undergone important advances. The combined results from atmospheric neutrino measurements, solar neutrino measurements and the long baseline experiments \[1\] imply the neutrino mass differences \(1.2 \times 10^{-3} < \Delta m^2_{23} < 4.8 \times 10^{-3} \text{ eV}^2\) and \(5.4 \times 10^{-5} < \Delta m^2_{12} < 9.5 \times 10^{-5} \text{ eV}^2\). However, there exists a serious problem in that the Los Alamos Liquid Scintillator Neutrino Detector (LSND) experiment \[2\] finds \(10 > \Delta m^2 > 0.2 \text{ eV}^2\) which is in serious conflict with the other results. It is possible that the LSND result is in error. The Mini-Boone experiment at Fermilab \[3\] is studying the appropriate region of parameter space and will be able to either confirm or rule out the LSND result. However, accepting the LSND result along with the limit on 3 light neutrino species from LEP-SLC measurements of Z\(^0\) decay implies the need for a sterile neutrino which has little or no interaction with the W and Z bosons \[4, 5\] (notwithstanding that a sterile neutrino poses a challenge to standard big bang nucleosynthesis calculations \[6\]). SNO neutral current data implies that \(\nu_\mu \rightarrow \nu_e\) must proceed via \(\nu_\mu \rightarrow \nu_\tau \rightarrow \nu_e\) \[4\] and while ruling out the pure \(\nu_\tau \rightarrow \nu_\tau\) transition allows as much as 40% admixture of sterile neutrino \[4\]. For the most part models of light sterile neutrinos have been introduced on purely phenomenological grounds to accommodate the LSND result in fits of neutrino mixing data without explaining it’s origins. In this paper we describe a mechanism which naturally explains a light sterile neutrino.

It is well known that the tiny mass of neutrinos can be related to the high mass scale of the right-handed Majorona neutrino via the see-saw mechanism which offers a natural explanation for the light SM neutrinos. The conventional see-saw mechanism does not explain why the sterile neutrino mass is so small. Some explanations are that the small sterile neutrino mass is related to the mechanism of supersymmetry breaking \[7\], that it is protected by a gauge symmetry \[8\], or by the introduction of yet more neutrinos in conjunction with a double see-saw mechanism \[9\]. In this note we propose the flipped see-saw mechanism which can naturally induce the small sterile neutrino mass. The idea is based on a natural extension of the SM that adds a 4th generation of fermions \[10, 11\]. The scenario we are proposing differs from the well known Hill-Paschos scenario \[10\] in that it induces a light right-handed Majorona neutrino and an electro-weak scale Majorona neutrino whereas the two Majorona neutrinos of the Hill-Paschos scenario both have electro-weak scale masses.

Heavy 4th generation chiral fermions are disfavoured by precision observables if one considers the contributions to the oblique parameters \[12\] \(S\) and \(T\) separately. The contributions to oblique parameters from possible new physics contributions have been classified into 3 cases \[13\]: (1) decreasing \(S\), (2) increasing \(T\), and (3) achieving \(S\) and \(T\) separately. The authors of Ref. \[14\], argued that the 4th generation SM-like fermions fall into case (2) and are consistent with precision measurements without requiring new physics. We analyze the oblique precision constraints on our scenario below.

The 4th generation neutrino scenario we propose is rather straightforward. We refer to it as the “flipped see-saw mechanism”. For simplicity we omit mixing with the other 3 generations. The light neutrino is then obtained via the mass matrix

\[
\frac{1}{2} \overline{\nu}_L \nu_R = \begin{pmatrix} M & D \\ D & 0 \end{pmatrix} \omega
\]

with

\[
\omega = \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix},
\]

where \(\nu_L\) and \(\nu_R\) are the left- and right-handed neutrinos of the fourth generation and \(\nu_L^c \equiv C(\overline{\nu}_L)^T\) is the (right-handed) charge conjugate field. Here D represents the usual Dirac mass term and \(M\) the left-handed Majorona mass term which is 0 in the normal see-saw mechanism. \(M\) can be induced via new dynamics. For example, \(SU(2)\) Higgs triplet fields \(\phi\) via \[15\],

\[
L = -G_\mu \overline{L} \tau. \phi L
\]

\]
with $L = (\nu_L, \ell_L)$. In this scenario the triplet vacuum expectation value is constrained by electroweak fits of the $\rho$ parameter to be small implying a large non-perturbative Yukawa coupling which we assume is due to new unknown physics. It should be emphasized that, the electroweak scale, $M$, may induce some difficulties in triplet models, so that the origin of $M$ might due to other unknown dynamics. The right-handed Majorana mass term is 0 in contrast to the large mass of the usual Majorana model which can be induced via extra symmetry for the right-handed neutrino.

The neutrino masses are obtained by diagonalizing the mass matrix and a small neutrino mass is obtained if $M \gg D$ and is given by

$$m_\nu \sim \frac{D^2}{M}$$

with mixing angle $\theta = D/M$. So for example, for $M = 200$ GeV and $D = 0.3$ MeV, $m_\nu = 0.9$ eV, which is in the range of the LSND result. This Majorana neutrino can easily escape the constraint from $Z^0$ decay data because of the $\theta^2$ suppression factor for left-handed couplings. The heavy neutrino mass is $m_N \sim M$, the electroweak scale.

This scenario differs from that of Hill and Paschos [10]. In the Hill-Paschos scenario if the Majorana mass term for right-handed neutrino, $M$, is the electroweak scale then $D$ must be of the same order as $M$ or else the induced light Majorana neutrino will show up in $Z^0$ decay. In the flipped see-saw mechanism the light Majorana neutrino almost totally decouples from the electroweak interaction. The heavy Majorana neutrino mass is of the order of the electroweak scale and should contribute to the oblique parameters $S$, $T$ and $U$.

We next consider the constraints we can put on 4th generation fermions using the Peskin-Takeuchi [12] parameterization of the oblique corrections, $S$, $T$ and $U$. Our definitions for $S$ and $U$ are slightly different from the original Peskin Takeuchi definitions in that we use the differences of the $\Pi$ rather than their first derivatives which has the benefit of eliminating the mass singularity. The oblique corrections are given by [12]:

$$S = -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2}$$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{x_w(1 - x_w)m_Z^2}$$

$$U = 16\pi \frac{[\Pi_{11}(m_Z^2) - \Pi_{11}(0)] - [\Pi_{33}(m_Z^2) - \Pi_{33}(0)]}{m_Z^2}$$

where $\Pi_{11}$ and $\Pi_{33}$ are the vacuum polarizations of isospin currents, and $\Pi_{3Y}$ is the vacuum polarization of one isospin and one hypercharge current, and $x_w = \sin^2 \theta_W$ with $\theta_W$ weak angle defined at $m_Z$.

The contributions to $T$ from the 4th generation leptonic sector in the limit $m_\nu \to 0$ and $\theta \to 0$ can be written [10]:

$$\Delta T = \frac{1}{16\pi^2} \frac{m_Z^2}{m_W^2}$$

where $m_E$ is the 4th generation charged lepton mass. The weakest constraint on $m_E$ is obtained when there is no quark contribution to $\Delta T$ which occurs for the case of degenerate 4th generation $U$ and $D$-type quarks. Using the most conservative value of $\Delta T < 0.6$ [14] results in the limit of

$$m_E < 210 \text{ GeV.}$$

For comparison the direct limit from LEP of $m_E > 100$ GeV would imply $\Delta T > 0.14$.

We can likewise use $S$ and $U$ to put constraints on 4th generation fermions where $m_N$ and $m_E$ enter as the masses of the lepton weak isospin doublet. $\Delta S$ and $\Delta U$ can be written as [10]:

$$\Delta S = \frac{\pi}{m_Z^2} \left\{ -2[Re\Pi_4(m_Z^2, m_N, m_N) - \Pi_4(0, m_N, m_N)] + 3Re\Pi_4^V(m_Z^2, m_E, m_E) - Re\Pi_4^A(m_Z^2, m_E, m_E) + \Pi_4^A(0, m_E, m_E) \right\}$$

$$\Delta U = 2\pi \left\{ -\frac{1}{m_W^2} \left[ Re(\Pi^V + \Pi^A)(m_W^2, m_N, m_E) - Re(\Pi^V + \Pi^A)(0, m_N, m_E) + \frac{2}{m_Z^2} Re\Pi_4^V(m_Z^2, m_E, m_E) \right] \right\} - \Delta S,$$

where

$$\Pi^{V,A}(q^2, m_1, m_2) = \frac{1}{12\pi^2} \left\{ \left[ q^2 - \frac{m_1^2 + m_2^2}{2} \pm 3m_1m_2 \right. \right.$$}

$$\left. - \frac{(m_1^2 - m_2^2)^2}{2q^2} \right] B_0(q^2, m_1^2, m_2^2) + m_1 \left[ -1 + \frac{m_1^2 - m_2^2}{2q^2} \right] B_0(0, m_1^2, m_1^2)$$

$$+ m_2 \left[ -1 + \frac{m_1^2 - m_2^2}{2q^2} \right] B_0(0, m_2^2, m_2^2)$$

$$\frac{q^2}{3} + \frac{(m_1^2 - m_2^2)^2}{2q^2} \right\}$$

(10)

with $B_0$ the standard scalar loop two-point function also given in ref. [10].

Fig. 1 shows $\Delta S$ and $\Delta U$ plotted as a function of the heavy Majorana neutrino mass, $m_N$, for $m_E = 100$, 150, and 200 GeV. While one can see that the present $U$ measurement of $U = 0.18 \pm 0.14(+0.01)$ [14] [17] does not constrain the neutrino mass, the $S$ parameter value of $S = -0.04 \pm 0.11(0.09)$ constrains $m_N$ to not be very large. This is especially true for heavy 4th generation quarks where degenerate chiral quarks contribute $\Delta S^q = 1/2\pi \approx 0.16$ in addition to a TeV Higgs boson.
which contributes $\Delta S \sim 0.15$ relative to the reference Higgs mass of 100 GeV \cite{13}. From these considerations it is unlikely that both heavy quarks and a heavy Higgs boson (say $M_H > 400$ GeV) exist. Likewise, the contributions to $\Delta S$ from heavy 4th generation quarks or a heavy Higgs boson leaves no room for further contributions from a heavy neutrino. However, a light neutrino, say less than 100 GeV for $m_E = 200$, can make a negative contribution to $S$ \cite{10} which would partially cancel the positive contributions from heavy quarks. It is therefore possible for the scenario of a heavy generation lepton and neutrino with $m \sim \mathcal{O}(100)$ GeV and 4th generation quarks to survive.

If we assume heavy, degenerate, 4th generation quarks and $M_H = 100$ GeV we obtain the allowed parameter space for $m_E$ and $m_N$ shown in Fig. 2 using the $S$ and $T$ values from Ref. \cite{14} and taking $U = 0$. As the Higgs mass increases the allowed region shrinks, mainly due to the Higgs contributions to $S$.

In this note we proposed a "flipped see-saw mechanism" for 4th generation neutrinos which naturally induces the light sterile Majorana neutrino needed to explain neutrino mixing measurements, in particular the LSND results. Constraints from existing high precision electroweak data implies a 4th generation of fermions which consists of

1. Two Majorana neutrinos, one which is nearly right-handed and light ($\leq 1$ eV) to account for the current neutrino data, and another which is nearly left-handed and with mass $M_Z/2 < M_N < 200$ GeV.
2. One charged lepton with $100 < M_E < 200$ GeV.
3. Two heavy (nearly) degenerate quarks with mass $\geq 200$ constrained by Tevatron search limits \cite{20}.

In addition to constraints from oblique parameters, 4th generation fermions can also affect other low energy processes such as $\bar{B}^0 - B^0$ and $K^0 - \bar{K}^0$ mixing, $b \to s\gamma$ etc. However, such effects are significantly suppressed by the small mixing between SM and 4th generation fermions. In general, the constraints on 3rd-4th generation mixing are looser than those on 1st-4th and 2nd-4th generation mixing. Constraints for mixing between 4th generation and SM fermions is reviewed in Ref. \cite{21}.

The key ingredient of this scenario will be tested in the near future by the Mini-Boone experiment \cite{3} which is searching for the appearance of an electron neutrino from muon neutrino in the process $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. If $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is not observed the model must be either improved or discarded. The remaining 4th generation fermions can be directly produced at both hadron and $e^+e^-$ colliders provided it is kinematically allowed. The search strategies will depend on the fermion mass and the size of the mixing with SM fermions. For example, in the lepton sector if the 3rd and 4th generation mixing angle, $\theta_{34}$, is not very small, then both $N$ and $E$ will decay via $N \rightarrow \tau W^*$ and $E \rightarrow \nu_e W^*$. If the angle is very small (of the order of $m_{\nu_e}/m_N$ or less), then the heavier one (either $E$ or $N$) will decay into the lighter, while the lighter one decays to SM normal fermions with a greatly suppressed rate\cite{21}. The situation is similar in the quark sector and the phenomenology of 4th generations can be found in Ref. \cite{21}. However a unique feature of the flipped see-saw model which should be pointed out is that the Higgs-neutrino coupling is proportional to $\sqrt{m_N m_N}/m_W$ in contrast to $m_N/m_W$ in conventional 4th generation models \cite{22}. This feature provides one possible method...
to distinguish these two models.

The effects of 4th generation fermions will also appear via virtual loops. The $ggH$ vertex is especially sensitive to heavy quarks which leads to an enhancement in the $gg \rightarrow H$ production rate which can be as large as a factor of $\sim 10$. Such effects might/must show up at upgraded Tevatron/LHC [23]. The enhancement due to heavy quarks will also occur in the $\gamma\gamma H$ vertex, which will impact, for example, the Higgs production rate at a $\gamma\gamma$ collider, as well as the intermediate mass Higgs searches at the LHC via $H \rightarrow \gamma\gamma$.

If the LSND result stands up to the scrutiny of the Mini-Boone experiment it may give the first evidence for the existence for a 4th generation of fermions.

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