Light unstable sterile neutrino

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(Received 20 July 2001; published 8 November 2001)

The three massless active (doublet) neutrinos may mix with two heavy and one *light* sterile (singlet) neutrino so that the induced masses and mixings among the former are able to explain the present data on atmospheric and solar neutrino oscillations. If the LSND result is also to be explained, one active neutrino mass eigenstate must mix with the light sterile neutrino, and the fit is improved if the latter also decays quickly enough to evade the CDHSW data. A specific model is proposed with the spontaneous and soft explicit breaking of a new global $U(1)_S$ symmetry so that a sterile neutrino will decay into an active antineutrino and a nearly massless pseudo Majoron.

Present experimental data [1–3] indicate that neutrinos oscillate. Hence they should have small nonzero masses and mix with one another. This may be achieved without additional fermions beyond those of the minimal standard model by a heavy Higgs triplet [4,5]. On the other hand, most theoretical approaches assume the addition of 3 singlet neutral fermions (usually considered as right-handed neutrinos N_R). In that case, a Dirac mass m_D linking the left-handed doublet neutrinos ν_L with N_R as well as a Majorana mass M for N_R are allowed, thus yielding the famous mass matrix

$$\mathcal{M}_{\nu N} = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}. \tag{1}$$

At this point, one may impose the conservation of lepton number as an additive global symmetry, i.e., $U(1)_L$, so that $M=0$; but then m_D would have to be extremely small, which is considered rather unnatural. The conventional solution of this problem is to not consider $U(1)_L$ at all so that M is naturally very large and since m_D cannot be larger than the electroweak breaking scale $v=(2\sqrt{2}G_F)^{-1/2}=174$ GeV, a small mass $m_\nu = m_D^2/M$ is obtained [6]. This of course requires M to be many orders of magnitude greater than v and renders it totally undetectable experimentally. Recently, it has been pointed out [7] that if m_D comes from a different Higgs doublet with a suppressed vacuum expectation value (VEV), then M may in fact be only a few TeV or less and become observable at future colliders.

In this Brief Report we consider the case where both m_D and M are small for *one* (call it S) of the three singlets, but m_D is still less than M by perhaps an order of magnitude. This is in contrast to the pseudo Dirac scenario [8], i.e. $M \ll m_D$, in which case neutrino oscillations would be maximal between active and sterile species, in disfavor with the most recent data [1,2]. Before discussing the theoretical reasons for m_D and M to be small, consider first the phenomenology of such a possibility. The 3 active neutrinos ν_e, ν_μ, ν_τ are now each a linear combination of 4 light neutrino mass eigenstates. With m_D less than M by an order of magnitude, the mixing of S with ν is still small; hence the presumably large mixings among the 3 active neutrinos themselves are sufficient to explain the atmospheric [1] and solar [2] neutrino data. This leaves the Liquid Scintillation Neutrino Detector (LSND) data [3] to be explained by having a neutrino mass eigenstate which is mostly S but with small amounts of ν_e and ν_μ. This is in fact the only motivation for our consideration, in the hope that the LSND result will be proven correct.

In addition to the one light S and the two heavy N's, we supplement the particle content of the standard model with a scalar singlet χ^0 and an extra scalar doublet $\eta=(\eta^+,\eta^0)$, together with a new global $U(1)_S$ symmetry such that (S,χ^0,η) have charges $(1,-2,-1)$, respectively. The reason for this added compexity is the theoretical difficulty of achieving a small mass for S as well as the mixing of S with ν_i. Even more difficult is to make S decay quickly. (In purely phenomenological discussions of sterile neutrinos, these important theoretical problems are simply ignored.) The relevant terms of the Lagrangian involving these fields are then given by

$$h\chi^0 SS + f_i S(\nu_i \eta^0 - l_i \eta^+) + \text{H.c.} \tag{2}$$

Using the canonical seesaw mechanism [6] with the two heavy N's, we obtain two massive neutrino eigenstates in the conventional way. The original 6×6 neutrino mass matrix is reduced to a 4×4 matrix spanning (ν_1, ν_2, ν_3, S). Its most general form is given by

$$\mathcal{M}_{\nu S} = \begin{bmatrix} 0 & 0 & 0 & \mu_1 \\ 0 & m_2' & 0 & \mu_2 \\ 0 & 0 & m_3' & \mu_3 \\ \mu_1 & \mu_2 & \mu_3 & M \end{bmatrix}, \tag{3}$$

where $M = 2h\langle\chi^0\rangle$ and $\mu_i = f_i\langle\eta^0\rangle$.

To obtain $\langle \eta^0 \rangle \sim 0.1$ eV, consider the part of the Higgs potential involving η, i.e.

$$V_\eta = m_\eta^2 \eta^\dagger \eta + \frac{1}{2} \lambda_1 (\eta^\dagger \eta)^2 + \lambda_3 (\eta^\dagger \eta)(\Phi^\dagger \Phi) + \lambda_4 (\eta^\dagger \Phi)$$
$$\times (\Phi^\dagger \eta) + [\mu_0^2 \eta^\dagger \Phi + \text{H.c.}], \tag{4}$$

where Φ is the usual standard-model Higgs doublet and the μ_0^2 term breaks $U(1)_S$ softly. The equation of constraint for $\langle \eta^0 \rangle = u$ is then given by

$$u[m_\eta^2 + \lambda_1 u^2 + (\lambda_3 + \lambda_4) v^2] + \mu_0^2 v = 0, \tag{5}$$

where $v = \langle \phi^0 \rangle$. For $m_\eta^2 > 0$ and large, we then have

$$u \simeq -\frac{\mu_0^2 v}{m_\eta^2}. \tag{6}$$

Let $m_\eta \sim 1$ TeV and $\mu_0 \sim 1$ MeV, we obtain $u \sim 0.1$ eV as desired.

To obtain $z = \langle \chi^0 \rangle \sim 1$ eV, we use the *shining* mechanism [9] of large extra dimensions, where χ^0 is assumed to exist in the bulk and its VEV on our brane is suppressed because of its distance from the source brane of $U(1)_S$ breaking. For consistency, the $\chi^0 SS$ interaction is replaced by $z \exp(i\sqrt{2}\varphi/z) SS$. This has been explained fully in a previous paper [10]. The important difference here is that $U(1)_S$ is also broken explicitly so that the would-be massless Goldstone boson φ, i.e., the Majoron [11,12], is not strictly massless. On the other hand, its mass may still be very small. We may call it a pseudo Majoron.

Returning to Eq. (3), we assume for definiteness a bimaximal pattern of mixing among the active neutrinos, i.e.,

$$\begin{bmatrix} \nu_1 \\ \nu_2' \\ \nu_3 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} & 1/2 & 1/2 \\ -1/\sqrt{2} & 1/2 & 1/2 \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}, \tag{7}$$

together with the *ansatz* that μ_1 and μ_3 are negligible. In that case, only ν_2' mixes significantly with S. The eigenstates are thus $\nu_2' \cos\theta + S \sin\theta$ with mass $m_2' - \mu_2^2/M \sim 0.007$ eV and $S \cos\theta - \nu_2' \sin\theta$ with mass $M \sim$ few eV, where $\sin\theta \simeq -\mu_2/M$. Hence the latter decays into the conjugate of the former and the pseudo Majoron with coupling $2\sqrt{2}h \sin\theta \cos\theta$. (If all μ_i's were of the same order of magnitude, the present observed neutrino oscillations cannot be explained, unless the 3 active neutrinos are almost degenerate in mass, requiring thus a high degree of unnatural fine tuning of parameters. Also, the nonzero overlap with S would make ν_3 and ν_2 decay into ν_1.)

The $\nu_\mu \to \nu_e$ probability in the LSND experiment is given by [13]

$$P_{\mu e} = \frac{s^4}{8} \left(1 + x^2 - 2x \cos\frac{M^2 L}{2E} \right) \sim 10^{-3}, \tag{8}$$

where $s = \sin\theta$ and $x = \exp(-M\Gamma L/2E)$ is the decay factor. (In the usual case of a stable sterile neutrino, $\Gamma = 0$ so $x = 1$.) The decay rate Γ is easily calculated to be

$$\Gamma = \frac{h^2 s^2 c^2 M}{2\pi} \simeq 0.18 M \left(\frac{h^2}{4\pi} \right) \left(\frac{s^2}{0.1} \right) \left(\frac{c^2}{0.9} \right), \tag{9}$$

which is of the right order of magnitude for it to be significant [13] in affecting the interpretation of the LSND data in terms of *both* oscillation and decay.

The 4×4 neutrino mixing matrix is now given by

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} & 1/2 & 1/2 & 0 \\ -c/\sqrt{2} & c/2 & c/2 & s \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} & 0 \\ s/\sqrt{2} & -s/2 & -s/2 & c \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ S \end{bmatrix}, \tag{10}$$

with $m_1 \simeq 0$, $m_2 \simeq m_2' - \mu_2^2/M \simeq 0.007$ eV, $m_3 \simeq m_3' \simeq 0.05$ eV, and $m_4 \simeq M \sim$ few eV. The phenomenology of this scheme for atmospheric and solar neutrino oscillations has been fully described previously [13]. We emphasize here the most important prediction of this model, i.e., the decay

$$\nu_4 \to \bar{\nu}_2 + \zeta, \tag{11}$$

where ζ is the pseudo Majoron. Since ν_e from the Sun has a ν_4 component, it will decay into $\bar{\nu}_2$ on its way to the Earth. The latter will be observed as $\bar{\nu}_e$ in detectors such as BOREXINO and perhaps SNO. The advantage of having ν_4 decay is to evade the indirect constraint from the CDHSW experiment [14] on the LSND allowed parameter space for neutrino oscillations. Numerical details are given in Ref. [13]. Without decay, the $(3+1)$ scheme of neutrino masses may be disfavored [15]. Note also that in our model, the pseudo Majoron does not couple to the active neutrinos, otherwise there would be significant bounds on the corresponding coupling strengths [16]. The decay of neutrinos from the Sun also applies to neutrinos from supernovae. Since the ν_4 component is small (of order 10^{-2}), its has no observable effect in that case.

The effective number of neutrinos N_ν for successful nucleosynthesis [17] is probably not greater than 4. In our scenario, it appears that $N_\nu = 4 + (8/7)$, counting as well S and χ^0. However, these two fields decouple from the standard-model particles at the scale M_η which we take to be 1 TeV. This means that whereas $\nu_{e,\mu,\tau}$ are heated by the subsequent annihilations of nonrelativistic particles, S and χ^0 are not [18]. Thus the number densities of the latter are greatly suppressed at the time of nucleosynthesis in the early Universe and $N_\nu < 4$ is easily obtained [19].

In conclusion, we have constructed a specific model in this short note in the framework of 3 active (doublet) and 3 sterile (singlet) neutrinos. Two of the latter are heavy, pro-

viding small seesaw masses for two active neutrinos. The third sterile neutrino is light and mixes with one of the massive active neutrinos. Together they allow all neutrino-oscillation data to be explained in a hierarchical pattern of neutrino masses. The light sterile neutrino is associated with a new global $U(1)_S$ symmetry which is spontaneously and softly broken, so that it decays into an active antineutrino and a nearly massless pseudo Majoron.

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