Custom-Designed Model of the 17-keV Neutrino

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A simple model is constructed which satisfies all the laboratory, astrophysical, and cosmological constraints discussed recently by Caldwell and Langacker for the possible existence of a 17-keV neutrino. It is mainly ν_τ, with $\bar{\nu}_\mu$ as its pseudo-Dirac partner, whereas ν_e is mainly a light pseudo-Dirac neutrino with an inert partner. The decay lifetime of the 17-keV neutrino is estimated to be 10 s or longer.

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With the reports [1,2] of two recent experiments, there has been a great resurgence of interest in the 17-keV neutrino first reported by Simpson [3], but not subsequently confirmed in other experiments [4] except two [5]. Whereas the experimental evidence remains controversial, theoretical and phenomenological implications of a possible 17-keV neutrino are clearly not without interest and there has been a flurry of activity [6–26] in this regard. In particular, Caldwell and Langacker [26] have considered all existing laboratory, astrophysical, and cosmological bounds and concluded that the 17-keV neutrino, if it exists, must be mainly ν_τ, and its contribution to neutrinoless double beta decay must be canceled by a massive ν_μ. It cannot be a Dirac neutrino with an inert partner, or else the ν_e pulse from the supernova 1987A would be very much shortened [27], and be in disagreement with observation [28]. To explain the apparent deficit of solar neutrinos observed on Earth, ν_e must convert into a new light neutrino which is inert.

It appears at first sight that it is very difficult to construct a model with the above requirements. Indeed, they are not met by any of the models that have been proposed so far, although most are certainly acceptable if one or more of the Caldwell-Langacker conditions are relaxed. However, as shown below, a simple model does exist which pairs ν_τ with $\bar{\nu}_\mu$ and ν_e with a new singlet state to form two pseudo-Dirac neutrinos in a way consistent with all laboratory, astrophysical, and cosmological constraints. The key to realizing the proposed scenario is to find a specific form of the neutrino mass matrix which yields the two desirable pseudo-Dirac mass eigenstates. This form must also be derivable from a symmetry, or else it would not be protected against large quantum corrections.

Let the standard SU(2)×U(1) electroweak gauge group be supplemented by a Z_5 discrete symmetry with elements 1, ω, ω^2, ω^{-2}, and ω^{-1}, with $\omega^5=1$. Let there be three lepton families, each consisting of a left-handed doublet $(\nu_i,l_i)_L$ and two right-handed singlets ν_{iR},l_{iR} and transforming as ω^{i-1} $(i=1,2,3)$ under Z_5. The scalar sector consists of two doublets, $(\phi_1^+,\phi_1^0)\sim 1$ and $(\phi_2^+,\phi_2^0)\sim\omega^{-2}$, and two singlets, $\chi_1^0\sim\omega^2$ and $\chi_2^0\sim\omega$. Furthermore, ν_i and l_i have lepton number $L=1$ and χ_i have $L=-2$. As a result, the 3×3 charged-lepton mass matrix linking $\bar{l}_{iL}$ to l_{jR} is of the form

$$M_l=\begin{bmatrix} a & 0 & d \\ 0 & b & 0 \\ 0 & 0 & c \end{bmatrix}, \tag{1}$$

whereas the 6×6 neutrino mass matrix linking $(\bar{\nu}_{iL},\nu_{jR})$ to itself is given by

$$M_\nu=\begin{bmatrix} 0 & 0 & 0 & A & 0 & 0 \\ 0 & 0 & 0 & 0 & B & 0 \\ 0 & 0 & 0 & D & 0 & C \\ A & 0 & D & 0 & 0 & 0 \\ 0 & B & 0 & 0 & 0 & E \\ 0 & 0 & C & 0 & E & F \end{bmatrix}. \tag{2}$$

The characteristic equation for M_ν is

$$\lambda^6-F\lambda^5-(A^2+B^2+C^2+D^2+E^2)\lambda^4+(A^2+B^2+D^2)F\lambda^3+[B^2C^2+D^2(E^2+B^2)+A^2(E^2+B^2+C^2)]\lambda^2 -(A^2+D^2)B^2F\lambda-A^2B^2C^2=0. \tag{3}$$

Note that if $A=0$, then M_ν has one zero eigenvalue. If $A=D=0$, then M_ν has two zero eigenvalues. If only $F=0$, then the six nonzero eigenvalues are of the form $\pm\lambda_{1,2,3}$ corresponding to three massive Dirac neutrinos. If $A=D=F=0$ and either $B=0$ or $C=0$, then M_ν has four zero eigenvalues. At each step, the symmetry of the neutrino sector is enlarged; it is thus natural [29] to consider the hierarchy

$$F,A\ll D\ll B,C,\ll E. \tag{4}$$

The eigenvalues of M_ν are then given by

$$\lambda_{1,2}=\pm A+D^2F/2C^2, \tag{5}$$

$$\lambda_{3,4}=\pm BC/E+B^2F/2E^2, \tag{6}$$

$$\lambda_{5,6}=\pm E+F/2, \tag{7}$$

where $D\ll BC/E$ has also been assumed. The mass eigenstates $n_{1,2,3,4}$ corresponding to $\lambda_{1,2,3,4}$ are

$$n_{1,2} \simeq \frac{1}{\sqrt{2}}\left(1, \pm\frac{DE}{BC}, -\frac{ADE^2}{B^2C^2}, \pm 1, \frac{ADE}{B^2C}, \mp\frac{D}{C}\right), \quad (8)$$

$$n_{3,4} \simeq \frac{1}{\sqrt{2}}\left(\frac{ADE^2}{B^2C^2}, \mp 1, 1, \pm\frac{DE}{BC}, -\frac{C}{E}, \pm\frac{B}{E}\right). \quad (9)$$

This means that $\nu_{3L}-(C/E)\bar{\nu}_{2R}+(ADE^2/B^2C^2)\nu_{1L}$ combines with $\bar{\nu}_{2L}-(B/E)\nu_{3R}-(DE/BC)\nu_{1R}$ to form a pseudo-Dirac neutrino which can be identified as having a mass of 17 keV. Let ν_{3L} be mostly ν_τ, then l_3 is mostly τ, but since l_3 mixes with l_1 but not l_2 in Eq. (1), l_1 should be mostly e and l_2 should be μ. Hence ν_{2L} is exactly ν_μ. On the other hand, $\nu_{1L}+(ADE/B^2C)\bar{\nu}_{2R}-(ADE^2/B^2C^2)\nu_{3L}$ combines with $\nu_{1R}-(D/C)\nu_{3R}+(DE/BC)\bar{\nu}_{2L}$ to form another pseudo-Dirac neutrino which is mostly ν_e, and hence its mass should be less than about 10 eV. Dropping the negligible components of $n_{1,2,3,4}$ in Eqs. (8) and (9), we then have

$$\nu_e \simeq \cos\theta\left(\frac{n_1+n_2}{\sqrt{2}}\right)+\sin\theta\left(\frac{n_3+n_4}{\sqrt{2}}\right), \quad (10)$$

$$\nu_\mu \simeq \frac{n_3-n_4}{\sqrt{2}}, \quad (11)$$

$$\nu_\tau \simeq \cos\theta\left(\frac{n_3+n_4}{\sqrt{2}}\right)-\sin\theta\left(\frac{n_1+n_2}{\sqrt{2}}\right), \quad (12)$$

where θ comes from the charged-lepton mass matrix of Eq. (1) and can be chosen to fit the result of the Oxford experiment [2], namely,

$$\sin^2\theta = 0.0085 \pm 0.0006 \pm 0.0005. \quad (13)$$

From Eqs. (5) and (6), we find

$$\Delta m_{12}^2 \simeq 2AD^2F/C^2 \quad (14)$$

and

$$\Delta m_{34}^2 \simeq 2B^3CF/E^3. \quad (15)$$

The best limit on Δm_{34}^2 comes from recent $\nu_\mu \to \nu_\tau$ oscillation data [30] which requires it to be less than 3.5×10^{-3} eV^2. Hence

$$\frac{F}{C^2}=\frac{1}{2}\left(\frac{E}{BC}\right)^3 \Delta m_{34}^2 < \frac{3.5\times10^{-3}\,\mathrm{eV}^2}{2(17\,\mathrm{keV})^3}$$
$$\simeq 3.6\times10^{-16}\,\mathrm{eV}^{-1}. \quad (16)$$

Since $\bar{\nu}_{1R} \simeq (n_1-n_2)/\sqrt{2}$ is inert, the conversion of ν_e into $\bar{\nu}_{1R}$ is a possible solution to the solar neutrino problem. However, the mixing here is exactly maximum ($\theta=45°$) which means that matter effects do not result in any level crossing and there is no Mikheyev-Smirnov-Wolfenstein solution [31] in this case. On the other hand, the long-wavelength solution [32] is still viable and for that Δm_{12}^2 should be of order 10^{-10} eV^2. For the purpose of illustration, let $A=5$ eV, $F=8$ eV, $D=200$ eV, $B=17$ MeV, $C=200$ MeV, and $E=200$ GeV, then $m(\nu_e)=5$ eV, $m(\nu_\mu,\nu_\tau)=17$ keV, $\Delta m_{12}^2 = 0.8\times10^{-10}$ eV^2, and $\Delta m_{34}^2 = 2\times10^{-3}$ eV^2. The effective ν_e mass for neutrinoless double beta decay is very much suppressed in this model. It is given by $(B^2F/2E^2)\sin^2\theta+(D^2F/2C^2)\cos^2\theta$, which is of order 10^{-10} eV for the above choice of parameter values. The smallness of F, A, and D in M_ν may be indicative of their possible origin as radiative corrections. Note also that $F=0$ corresponds to the symmetry $L_e-L_\mu+L_\tau$. In the scalar sector, where $L=L_e+L_\mu+L_\tau$ is only spontaneously broken, Z_5 is also broken explicitly by soft terms [33].

Consider now the decay of the 17-keV neutrino. Since lepton number is spontaneously broken by $\langle\chi_i^0\rangle$ in this model, there exists a massless Goldstone boson called the Majoron which is a linear combination of $\chi_{1,2}^0$ and $\bar{\chi}_{1,2}^0$. Being all SU(2) singlets [34], they do not contribute to the invisible width of the Z boson and are thus consistent with the conclusion from experiments at the CERN e^+e^- collider LEP that the effective number of light neutrinos is just three [35]. Using Eqs. (2), (8), and (9), we find that $n_{3,4}$ do couple to $n_{1,2}$ through χ_i^0; hence the decay $n_{3,4} \to n_{1,2}+$Majoron is allowed. For a $\chi_1\nu_{2R}\nu_{3R}$ coupling of order unity, the effective coupling for the decay is approximately D/E, which is of order 10^{-9}. Hence the decay lifetime of the 17-keV neutrino is roughly 10 s. This time is long enough so that the Majoron will not affect nucleosynthesis in the early Universe; it is also short enough so that the 17-keV neutrino will contribute very little to the relic density of the Universe and may even be useful in understanding galaxy formation. The inert pseudo-Dirac partner of ν_e is also cosmologically safe because the oscillation time between it and ν_e is of order 10^2 s at an energy of 10 MeV. The supernova bound [27] on the mass of a heavy Dirac neutrino is not applicable here because no component of the 17-keV neutrino is inert.

In conclusion, a simple model has been presented where a Z_5 discrete symmetry is used to obtain the specific forms of M_l and M_ν of Eqs. (1) and (2). Given these forms, the scenario for a safe 17-keV neutrino as discussed by Caldwell and Langacker [26] is realized. It is mainly ν_τ, with $\bar{\nu}_\mu$ as its pseudo-Dirac partner, whereas ν_e is mainly a light pseudo-Dirac neutrino with an inert partner. The decay lifetime of the 17-keV neutrino is estimated to be of order 10 s if the $\chi_1\nu_{2R}\nu_{3R}$ coupling is of order unity. The solar neutrino problem is solved here by the long-wavelength vacuum-oscillation scenario [32] with ν_e converting to $\bar{\nu}_{1R}$, which can be tested experimentally in the near future.

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