Massive neutrinos in a Calabi-Yau model

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We present an extension of the standard neutrino sector motivated by the heterotic string. Its basic ingredients are two nonweakly interacting neutrinos and a Z_3 discrete symmetry acting as a matter parity. Although this model represents a very minimal extension of the standard model, its *flexibility* to produce nonstandard effects in a way consistent with the constraints from cosmology, astrophysics, and particle physics phenomenology seems quite remarkable. In particular, we discuss the ability of the model to accommodate the various experimental anomalies (τ lifetime, 17 keV neutrino, and solar-neutrino deficit) which have been the object of recent controversy.

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The study of neutrino physics has attracted renewed interest during the last years. In addition to the progress in Z^0 and τ physics, cosmology and astrophysics appear to be increasingly sensitive to the physics in the neutrino sector. Although there is no definitive signal of new physics, there are some experimental anomalies that have been (and still are) the object of controversy. If not really significant, these anomalies give us a hint of the type of nonstandard effects that one could still expect to find at low energies.

First, the τ-Fermi coupling (G_τ) measured in τ decays seems to be slightly smaller than the one corresponding to the other two families ($G_{e,\mu}$). According to recent [1] results from the CERN e^+e^- collider LEP $G_\tau/G_{e,\mu}=0.977\pm0.010$, while the DELPHI Collaboration found that $G_\tau/G_{e,\mu}=0.967\pm0.023$, in both cases a 2σ deviation that cannot be considered too disturbing yet. Probably this and other puzzles in τ physics will be clarified in the near future (projected τ-charm factory) but, in principle, such a discrepancy would suggest that the τ neutrino has a sizable component along a field heavier than the τ lepton, and thus the τ decay to this field plus virtual W^- is forbidden kinematically. To implement such an effect, however, will not be easy, since it requires extra physics in a range of energies (~1 GeV), where the minimal standard model (SM) appears very solid, especially after LEP.

The second anomaly was observed by Simpson in the β decay of tritium [2], and it was interpreted as a 17-keV neutrino containing a 10% of electron flavor. The mass of this field would make it especially relevant in cosmology and astrophysics, as well as in nuclear physics experiments [3], and up to now no completely satisfactory model to accommodate it has been found. Although no other possible explanations of this anomaly have been found yet, the evidence for a conventional neutrino as its origin is becoming weaker, and recent negative results seem quite conclusive [4].

Finally, there is the observed deficit in the flux of neutrinos coming from the Sun [5]. It is possible to explain this deficit through the Mikheyev-Smirnov-Wolfenstein (MSW) effect [6] if the neutrinos had masses of order 10^{-3} eV and sizable mixings among them. Such a scenario is naturally predicted by the seesaw mechanism [7], and the problems only show up when one tries to make it consistent with any of the other two effects.

From the model building point of view, the seesaw mechanism appears as a suitable extension of the SM, following in most of the grand unified theory (GUT) scenarios. However, it involves fields in nonchiral representations of the SM symmetry, and the masses of order 1 GeV required to explain the possible discrepancy in the τ lifetime or the Simpson anomaly seem difficult to justify. In addition, in minimal seesaw scenarios (extensions with only right-handed neutrinos and no additional symmetries) it is not possible to get mixings of order 10^{-1} between the light and the heavy neutrinos (necessary to solve these anomalies) without giving to the former masses in conflict with standard cosmology.

We would like in this Brief Report to present a model where the field content, the scales, and also the zeros in the neutrino mass matrix are motivated by the heterotic string. The model includes two sectors: the three weakly interacting (WI) neutrinos, plus two non-weakly-interacting (NWI) fields. It predicts one heavy Dirac field (defined basically from the two-gauge singlets) and three massless neutrinos. Remarkably, the model allows sizable mixings between the two sectors, while keeping these neutrinos massless. For different values of the parameters in the model, we will study its possible relevance in explaining a longer τ lifetime and the Simpson anomaly. We will also study the possibility of implementing in this model the masses required to solve the solar neutrino problem through the MSW effect.

The model. In the framework of the heterotic string compactified in a Calabi-Yau (CY) manifold [8] one is left at very high energies with an effective supersymmetric (SUSY) GUT. The resulting unified gauge symmetry will be a rank-six subgroup of E_6 (for example, $[SU_3]$ [3]), while the chiral superfields will lay in multiplets included in the **27**, $\overline{\mathbf{27}}$, and **1** representations of this group. To obtain a viable limit, the evolution down to low energies must provide very large intermediate scales (IS's) of symmetry breaking, where the model is reduced to (essentially) a minimal SUSY extension of the SM. These IS's will be defined by vacuum expectation values (VEV's) of the ν_4 and ν_5 gauge flavors in two $27+\overline{27}$ vectorlike multiplets (see Ref. [9] for notation and a detailed discussion). The suppression of lepton- and baryon-number-violating processes requires that the VEV's leave unbroken a (generalized) matter parity (MP) [10], that will arise as a suitable combination of a gauge and a discrete symmetry of the compactified model. In the IS's, four of the eight NWI neutrinos in the two $27+\overline{27}$ multiplets combine with gauginos associated with lost symmetries and become massive. The four remaining will have model-dependent masses, defining a pattern that can vary from four massless neutrinos (the case with exact flat directions and no mixing with E_6 singlets) [11] to one light [~ 1 TeV] field plus three neutrinos at intermediate energies [$\gtrsim 10^5$ GeV] [9]. The Yukawa couplings of two of these NWI neutrinos with the rest of the low-energy fields are necessarily very suppressed, so we are left with just two relevant singlets.

Unbroken matter parities would appear naturally in CY models because the required flatness of the scalar potential favors IS's with a certain symmetry (in any case, MP is a necessary phenomenological requirement in SUSY models). From the two inequivalent Z_3 MP's defined in SUSY models, only one (corresponding to the case that we will consider) is realized in the three-generation CY manifold of Tian and Yau [10]. This Z_3 discrete symmetry will put zeros in the *extended* (by the two singlets) neutrino mass matrix. With the assignments of Z_3 numbers in Table I, the only allowed (renormalizable) terms in the superpotential (P) are

$$P=P_{\rm SM}+MN_1N_2^c+y_i\begin{pmatrix}e\\ \nu\end{pmatrix}_i N_2^c\begin{pmatrix}h^0\\ h^+\end{pmatrix}+\lambda_1N_1^3+\lambda_2N_2^{c3}\ , \quad (1)$$

where $P_{\rm SM}$ contains the terms necessary to give masses to standard quarks and leptons (h^0 and h'^0 interact with *up* quarks and charged leptons and *down* quarks, respectively). The fermionic components of the superfields in Eq. (1) are two-component spinors of (by convention) left-handed chirality.

When the Higgs scalars h^0 and h'^0 develop VEV's, the neutrino mass matrix becomes

$$L_{m_\nu}=(\nu_1\ \ \nu_2\ \ \nu_3\ \ N_1\ \ N_2^c)\begin{pmatrix}0&0&0&0&m_1\\0&0&0&0&m_2\\0&0&0&0&m_3\\0&0&0&0&M\\m_1&m_2&m_3&M&0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ N_1\\ N_2^c\end{pmatrix}+\text{H.c.} \quad (2)$$

TABLE I. Z_3 matter parity ($\alpha^3=1$).

Field	Z_3	Field	Z_3
$(e\nu)_i$	1	(h^0h^+)	α^2
e_i^c	α^2	$(h'^-h'^0)$	α
$(ud)_i$	1	N_1	α^2
u_i^c	α	N_2^c	α
d_i^c	α^2		

All terms in this matrix are Dirac type. After diagonalizing it, we find that the (prime) mass eigenstates are

$$\begin{pmatrix}\nu_1'\\ \nu_2'\\ \nu_3'\\ N_1'\\ N_2^{c\prime}\end{pmatrix}=\begin{pmatrix}c_\alpha&-s_\alpha&0&0&0\\ s_\alpha c_\beta&c_\alpha c_\beta&-s_\beta&0&0\\ s_\alpha s_\beta c_\theta&c_\alpha s_\beta c_\theta&c_\beta c_\theta&-s_\theta&0\\ s_\alpha s_\beta s_\theta&c_\alpha s_\beta s_\theta&c_\beta s_\theta&c_\theta&0\\0&0&0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ N_1\\ N_2^c\end{pmatrix}, \quad (3)$$

where $s_\alpha\equiv\sin\alpha$, $c_\alpha\equiv\cos\alpha,\ldots$ and $\tan\alpha=m_1/m_2$, $\tan\beta=\sqrt{m_1^2+m_2^2}/m_3$, and $\tan\theta=\sqrt{m_1^2+m_2^2+m_3^2}/M$. All complex phases may be absorbed by field redefinitions.

The states ν_1', ν_2', and ν_3' are massless (for all values of the parameters), while N_1' and $N_2^{c\prime}$ will define a Dirac neutrino of mass $M'=\sqrt{m_1^2+m_2^2+m_3^2+M^2}$. The angle θ fixes the mixing between the weak and the NWI neutrino sectors. Since ν_1', ν_2', and ν_3' are mass degenerated, it is still possible to perform rotations in the space defined by these fields and thus to reduce the mixing between the (basically) three standard neutrinos to $O(\theta^2)$. The charged and neutral currents involving mass eigenfields are then easily obtained, resulting in the *exotic* weak transitions $\overline{e_i}\sigma^\mu\nu_j'$ $(i\neq j)$ with a coupling of order θ^2, $\overline{e_i}\sigma^\mu N_1'$ of $O(\theta)$, $\overline{\nu_i'}\sigma^\mu\nu_j'$ $(i\neq j)$ of $O(\theta^2)$, $\overline{\nu_i'}\sigma^\mu N_1'$ of $O(\theta)$, and $\overline{N_1'}\sigma^\mu N_1'$ of $O(\theta^2)$. In addition, the trilinear N_1^3 [see Eq. (1)] induces in P terms $N_1'N_1'\nu_i'$ of $O(\theta)$ and $N_1'\nu_i'\nu_j'$ of $O(\theta^2)$ that may be of some relevance.

Although the proposed scenario is not a necessary consequence of CY models, its *stringy* character appears quite well defined, making interesting the study of its possible phenomenological consequences. This model for the neutrino sector belongs to the class of models in which additional global or discrete symmetries protect the three neutrinos from acquiring mass, which (with other motivations) have been extensively considered [12,13]. In particular, a neutrino mass matrix with six extra fields but with basically this structure was first proposed by Wolfenstein and Wyler [13].

A longer τ lifetime. The model could explain such an effect if the parameters in Eq. (1) verify $m_3\gg m_1,m_2$ (only the τ neutrino ν_3 mixes with N_1) and $M'>m_\tau$. In that case ν_3 will be an admixture of the massless ν_3' and the heavy N_1':

$$\nu_3=c_\theta\nu_3'+s_\theta N_1'\ . \quad (4)$$

Then, the τ decay to N_1' plus virtual W^- will be forbidden kinematically, and the τ lifetime (and the effective G_τ^{-2}) will increase by a factor c_θ^{-2}. The mixing favored experimentally would be $s_\theta\sim 0.2$. (A complete analysis of the incidence in precision tests of the SM of heavy neutral singlets that mix with the three chiral neutrinos has been performed in Ref. [14]. There it is shown that such a mixing in the τ sector seems certainly favored.)

As mentioned in the preceding section, in this scenario the neutrino neutral currents expressed in terms of mass eigenstates are not diagonal:

$$Z^0_\mu \overline{\nu_3}\sigma^\mu\nu_3 = Z^0_\mu[c^2_\theta\overline{\nu'_3}\sigma^\mu\nu'_3 + s^2_\theta\overline{N'_1}\sigma^\mu N'_1 + s_\theta c_\theta(\overline{\nu'_3}\sigma^\mu N'_1 + \overline{N'_1}\sigma^\mu\nu'_3)] \quad (5)$$

(the nondiagonal terms are absent in four-family models). This fact has consequences in Z^0 physics that will depend on the mass M' of N'_1. For $M' > M_Z$, no N'_1 neutrinos are produced in Z^0 decays. In this case the invisible width of the Z^0 boson associated with the decay to a pair of τ neutrinos is reduced by a factor c^4_θ, and the effective number of neutrino species (N_ν) measured in Z^0 factories should be slightly smaller than three: $N_\nu \sim 3 - 2s^2_\theta = 2.92$ for $s_\theta = 0.2$.

For $M' < M_Z/2$, the neutrino N'_1 is produced in Z^0 decays:

$$Z^0 \to N'_1 + \overline{N'_1} \; , \quad (6a)$$

$$Z^0 \to N'_1 + \overline{\nu}'_3 \; . \quad (6b)$$

The process in Eq. (6b) is also possible in the regime $M_Z/2 < M' < M_Z$. The subsequent decay of this field will depend on the relative importance of the interactions derived from $\lambda_1 N^3_1$ in P. For small couplings λ_1 and/or heavy *sneutrinos* $\tilde{N}_1$, the electroweak interactions are the dominant, and N'_1 decays into $\tau^- W^+$ and $\nu'_3 Z^0$ (the weak bosons are virtual) with an effective Fermi coupling $G_{N'_1} = s_\theta G_{e,\mu}$.

The decay of the Z^0 boson to two heavy neutrinos has been investigated at SLAC [15] and LEP [16] (in the framework of four-family models), with negative results. Here, however, the limits coming from pair production of heavy neutrinos (a process suppressed by a factor $s^4_\theta \sim 10^{-3}$) are much weaker, while indirect search (invisible width of the Z^0) does not apply. This makes the quoted searches not accurate enough. In the present model the dominant source of N'_1 leptons would be the Z^0 decay to a heavy and a massless neutrino [in Eq. (6b)], whose branching ratio is only suppressed by a factor s^2_θ. We are not aware of any published search of this kind of events at SLAC or LEP, although some preliminary results from the $L3$ Collaboration [17] do not show any significant signal.

In any case, there is a natural way to make this neutrino invisible in Z^0 factories even though it is significantly produced (accompanied with a massless neutrino) and decays inside the detectors. This would happen if the processes to three τ neutrinos involving its (virtual or real) SUSY partner $\tilde{N}_1$ dominated the weak decays. Since the relative rate of these processes is very sensitive to the mass ratio of the exchanged boson (it is proportional to $(M_Z/M_{\tilde{N}_1})$ [4]), values of M' below M_Z would not be excluded but would require, for reasonable couplings λ_1, the existence of a scalar $\tilde{N}_1$ also lighter than the Z^0 boson.

Simpson anomaly. To explain a 17-keV neutrino in this scenario the parameters must fix $M \sim 17$ keV and $s_\theta \sim 0.1$, with $m_1 \gg m_2, m_3$ (the dominant mixing is now with the electron neutrino). The anomaly would be due to a Dirac neutrino that mixes with ν'_1 and that contains a left-handed component (N'_1), which is weakly interacting (with a gauge coupling reduced by a factor s_θ) and a right-handed component (N'_2), which is sterile.

Reasonable models for the 17-keV neutrino have to deal with unobserved neutrinoless double β decays, cosmological constraints for its lifetime and for its abundance at the time of primordial nucleosynthesis, and limits from fast cooling in supernova explosions. Although our study here will be far from complete, we would like to mention the answers provided by the present model to the questions above. (Models for the 17-keV anomaly with only right-handed neutrinos have been considered in Ref. [18].)

Neutrinoless double β decay [6] is absent in this model, since there are not Majorana mass terms (the heavy neutrino is a Dirac field).

For the fast decay necessary to avoid an overclosed universe [3,18], we check whether the tree-level process mediated by a virtual Z^0 boson to three massless neutrinos is enough. We find that the predicted lifetime, around 10^{14} s, is still far from the acceptable upper limit of 10^{11} s. In addition, the one-loop electroweak process to $\gamma\nu_1$ is predicted with a branching ratio of $\sim 10^{-2}$, while experimentally it must be smaller than 10^{-5} (extragalactic ultraviolet background) [19]. These two problems are simultaneously solved if the decay of N'_1 to three electron neutrinos via $\tilde{N}_1$ were the dominant one and reduced the weak branching ratio to less than 10^{-3}. As discussed in the previous section, this rate is easily obtained for scalars $\tilde{N}_1$ lighter than the Z^0 boson. Since this scalar is neutral, it does not increase the decay to $\gamma\nu$ and the branching ratio of this process would also be reduced to allowed values.

The constraints from primordial nucleosynthesis arise because the 17-keV neutrino introduces new light fields in thermal equilibrium at 1 MeV, increasing the predicted abundance of ^{4}He. In the model under study here, the number of neutrino species in equilibrium at the time of nucleosynthesis is four (the three massless plus N'_1), which is in the limit given by the observed primordial ^{4}He mass fraction [the reported limit of 3.4 neutrino species is based on the few conservative assumption $Y_p(^4\text{He}) < 0.24$] [20]. The sterile component N^c_2 of the Simpson neutrino does not contribute, since for a Dirac mass term of 17 keV its relative abundance at temperatures around 1 MeV is negligible. In any case, it may be possible (if not necessary) to tune the mass and the lifetime of the scalar $\tilde{N}_1$ in order to reduce the predicted abundance of ^{4}He, which could be changed by the influence of the electron neutrinos resulting from the decay of this scalar [21].

Finally, we will consider the supernova bounds on the Dirac mass present in this model. The scattering of neutrinos and nucleons in the supernova core would produce helicity flipping (conversion of left-handed neutrinos into N'_2). The constraint to this process appears because the (sterile) right-handed field would escape from the core and thus could cool it too fast. The commonly accepted upper limit for the mass of a Dirac WI neutrino is around 14 keV [22]. In the model we are considering, however, the left-handed field N'_1 interacts weakly with an effective coupling that is s_θ times smaller [see Eq. (5)]. This pushes the disturbing limits for the mass far away from the desired value: $M' < 14 s_\theta^{-1}$ keV ~ 140 keV.

Solar neutrino problem. As explained before, the model predicts zero masses for the (basically) three standard neutrinos, and thus it needs some mechanism to implement the small ($\sim 10^{-3}$ eV) masses required by the MSW effect. One may expect to generate these masses by superposing a seesaw mechanism with the heavy fields present in CY models. However, this is not the case, and as long as the Z_3 matter parity is unbroken the three neutrinos remain massless. There is, nevertheless, the possibility of breaking the discrete symmetry via VEV's of the scalar $\tilde{N}_1$. The trilinear $\lambda_1 N_1^3$ in P would then induce a Majorana mass $m' N_1 N_1$ that increases the rank of the mass matrix and makes massive one of the three standard neutrinos (this term would also generate [23] at two-loop level smaller masses for the other neutrinos).

Assuming that $M \gg m \gg m'$, in a first approximation the new mass matrix will have two eigenstates (N_1' and $N_1^{c\prime}$) with masses of order M, another (ν_h', with h equal 1 and 3 for the Simpson and τ anomalies, respectively) with a mass of order $m' m^2 / M^2$, where $m^2 \equiv (m_1^2 + m_2^2 + m_3^2)$, plus two massless fields. The mixing between N_1 and the weak neutrinos would be of order m_i / M, while the mixings between ν_h' and $\nu_{i \neq h}'$ and between the two massless neutrinos are of order m_i / m_h and $(m/M)^2$, respectively. To accommodate a neutrino mass of order 10^{-3} eV together with the Simpson neutrino or a longer τ lifetime, m' should be (in both cases) of order 10^{-1} eV, a small value that does not alter any of the arguments used in previous sections.

Our conclusions are the following. We have presented a superstring-motivated model whose ability to deal with many different constraints would make it, if the discussed anomalies (or another similar) were confirmed, an interesting possibility. Although this model is a minimal extension of the SM, we have not found it in previous literature. We find, however, a precedent in the model with global symmetries and six extra singlets studied in Refs. [14–16], which provides a neutrino mass matrix with the same structure and offers the possibility of mixings while keeping three neutrinos massless. Our model also incorporates a way to give mass to one of these neutrinos and thus explain the solar neutrino problem.

Note added. A matrix with the same structure as the one resulting here after breaking the Z_3 symmetry (used to explain the solar neutrino problem) was first proposed in Ref. [24], in the framework of Z' models. I thank R. N. Mohapatra for pointing this out to me.

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