Is There Any Evidence for a Heavy Neutral Fermion ($\nu_{(\tau)R}$)?

F. del Aguila,(1) G. L. Kane,(2) J. M. Moreno,(3) and M. Quirós(4)
(1)*Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*
(2)*Randall Physics Laboratory, University of Michigan, Ann Arbor, Michigan 48109*
and Superconducting Super Collider Laboratory, Dallas, Texas 75261
(3)*Departement de Physique Thorique, Universit Libre de Bruxelles, Boulevard du Triomphe,*
CP 225, B-1050 Bruxelles, Belgium
(4)*Instituto de Estructura de la Materia, Serrano 119, E-28006 Madrid, Spain*

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In the standard model a right-handed neutrino can appear only by mixing with the left-handed neutrinos. Precise electroweak data constrain this mixing. We consider models in which the mixing is not proportional to neutrino masses. We have analyzed data and constraints on m_t, m_H with and without mixing ($\sin\epsilon$) of neutrinos with new inert fermions. For universal ν mixing, $\sin\epsilon = 0.09$; if only ν_τ mixes, $\sin\epsilon_\tau = 0.22$. Thus ν_τ data, $\Gamma\tau$ and Γ_Z^{inv}, if interpreted without caution, perhaps favor a nonzero ν_τ mixing and the existence of heavy neutral fermions.

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As is well known by now, the only *trouble* with the minimal standard model (MSM) is that it agrees extremely well with experiment.[1,2] Thus if any new physics should show up, its effects on present data should be very small. For instance, the existence of new gauge interactions mediated by a new Z' is excluded at the present accuracy by the low-energy set of data, at least in the minimal gauge extension of the standard model.[1,3] The presence of light extra matter is also excluded.[4] In particular, data from the CERN e^+e^- collider LEP seem to approach the MSM predictions from *below*, which translates into stringent bounds on new light matter (below stands for cross sections smaller than expected). If data stay below the MSM predictions as errors decrease, it would imply smaller gauge couplings of the known light matter and/or its mixing with new heavy matter with weaker standard-model interactions.

Mixing of the fermions of the three families with new quarks and leptons could be considered in an *ad hoc* way, but it is somewhat better motivated, and simpler, to consider mixing with SU(2) singlet quarks and right-handed neutrinos, both of which occur in E_6 fermion representations. Interestingly enough, the values of Γ_Z^{inv} and $\Gamma(\tau \to e, \mu, \ldots)$, which are the only pieces of data involving ν_τ, show a tendency to lie below the MSM expectations. Other data show a very good agreement with the MSM predictions, so we will not consider quark mixing further here.[5] In this Letter we examine the quantitative significance of a ν_τ mixing, $\sin\epsilon_\tau$, for present low-energy data, and also a universal ν mixing, $\sin\epsilon$. Other parametrizations could be used, of course, but these represent the possibilities well.

The present level of experimental accuracy requires, when comparing the electroweak theory with experiment, the inclusion of radiative corrections.[6] These corrections, and also the very comparison, depend on the specific model. To be definite and to test only the mixing hypothesis, we use for our fits the model in Ref. 3, with $M_{Z'}$ very large, where the complete one-loop expressions are available. In this model the neutrino mass matrix reads

$$\mathcal{M} = \begin{pmatrix} 0 & a\langle h^{0*}\rangle & 0 \\ a\langle h^{0*}\rangle & 0 & b\langle \tilde{\nu}_L^{c*}\rangle \\ 0 & b\langle \tilde{\nu}_L^{c*}\rangle & 0 \end{pmatrix}, \qquad (1)$$

where h^0 is the Higgs scalar of the minimal electroweak model and the different entries (ν_L, ν_L^c, N) are 3×3 matrices, corresponding to three generations. This mass matrix comes from adding to the MSM an SU(2) singlet right-handed neutrino (ν_L^c) and a totally neutral fermion (N) per family.[7] In this model $B-L$ is gauged, avoiding any problem with broken global symmetries. The new gauge boson is assumed to be very heavy, $M_{Z'} \sim \langle \tilde{\nu}_L^c\rangle \to \infty$, and we will ignore it. [A neutral Higgs singlet with the quantum numbers of the right-handed neutrino ($\tilde{\nu}_L^c$) enlarges the Higgs sector and gives mass to Z'.] The mixing $b^{-1}a\langle h^{0*}\rangle/\langle \tilde{\nu}_L^{c*}\rangle$ may be sizable.

The interest of this model for us is the neutrino mass matrix in Eq. (1). It corresponds to three Dirac heavy neutral fermions and three massless neutrinos $\nu_{Li} - (b^{-1}a)_{ji}(\langle h^{0*}\rangle/\langle \tilde{\nu}_L^{c*}\rangle)N_j$. If only the right-handed neutrinos were added, the upper-left 6×6 matrix would imply massive left-handed neutrinos ($a\langle h^{0*}\rangle$ large) or practically massless right-handed neutrinos ($a\langle h^{0*}\rangle$ small), with no effect on the data we want to analyze, or massive Majorana right-handed neutrinos, if a large Majorana mass is added to the lower-right $\nu_L^c \nu_L^c$ entries, and light left-handed neutrinos with seesaw masses. In this case the mixing is naturally proportional to the light masses and then very small. To have massless neutrinos and nonzero mixing (and hence to separate both effects) a simple solution is provided by Eq. (1), which is also a result of the symmetries of the model. In this way, the light spectrum of the model is that of the MSM but with the massless neutrinos mixed with totally neutral states.

TABLE I. χ^2 fit to neutral-current data, M_W, and Z and τ decay rates for the cases of no mixing, universal ν mixing, and ν_τ mixing. α, G_μ, and M_Z are fixed to their experimental values. m_t, m_H, and (eventually) the mixing angle are free parameters. The preferred values of the fitted quantities and the central values of the free parameters correspond to the minima of the χ^2 distributions.

Process	Quantity	Experimental value	(χ^2 contribution at the minimum) Preferred value		
			No mixing	Universal ν mixing	ν_τ mixing
Deep	$\Delta\chi^2(\nu q)$		(5.5)	(5.1)	(5.5)
Inelastic	g_L^2	0.2977±0.0042	0.3035	0.3025	0.3035
ν–Hadron	g_R^2	0.0317±0.0034	0.0299	0.0294	0.0299
	θ_L	2.50±0.03	2.46	2.46	2.46
	θ_R	4.59±0.44	5.18	5.18	5.18
Elastic	$\Delta\chi^2(\nu_\mu e)$		(0.2)	(0.2)	(0.2)
$\nu_\mu e$	g_A^e	-0.513±0.025	-0.506	-0.504	-0.506
	g_V^e	-0.045±0.022	-0.038	-0.041	-0.038
Deep	$\Delta\chi^2(eq)$		(0.8)	(0.9)	(0.8)
Inelastic	C_{1u}	-0.253±0.071	-0.206	-0.200	-0.206
e–Hadron	C_{1d}	0.391±0.064	0.349	0.347	0.349
	$C_{2u}-\frac{1}{2}C_{2d}$	0.22±0.36	-0.09	-0.07	-0.09
W	$\Delta\chi^2(M_W)$		(0.5)	(1.0)	(0.5)
Production	$M_W(GeV)$	80.6±0.4	80.3	80.2	80.3
Z	$\Delta\chi^2(\Gamma_Z^{inv})$		(1.4)	(0.7)	(0.0)
Decay	$\Gamma_Z^{inv}(MeV)$	482±16	501	495	485
	$\Delta\chi^2(\Gamma_Z^{\ell})$		(0.1)	(0.3)	(0.1)
	$\Gamma_Z^{\ell}(MeV)$	83.9±0.7	83.7	84.3	83.7
	$\Delta\chi^2(\Gamma_Z^{had})$		(2.4)	(0.5)	(2.4)
	$\Gamma_Z^{had}(MeV)$	1764±16	1739	1753	1739
τ	$\Delta\chi^2(\Gamma(\tau\rightarrow e,\mu))$		(2.5)	(2.5)	(0.2)
Decay	$\Gamma(\tau\rightarrow e)(10^{-13}GeV)$	3.845±0.192	4.115	4.115	3.916
	$\Gamma(\tau\rightarrow \mu)(10^{-13}GeV)$	3.867±0.192	4.003	4.003	3.809
Total χ^2/DOF			13.35/13	11.05/12	9.74/12
Central value					
$m_t(GeV)$			153	120	153
$m_H(GeV)$			90	150	90
$\sin\epsilon_{(\tau)}$			–	0.09	0.22

We will distinguish three cases: $(b^{-1}a)_{ji}\langle h^{0*}\rangle/\langle\tilde{\nu}_L^{c*}\rangle=0$ (MSM), $=\sin\epsilon\delta_{ji}$ (universal mixing), and $=\sin\epsilon_\tau\delta_{j3}\delta_{i3}$ (ν_τ mixing). Mixing with right-handed neutrinos has been considered very generally before[4,8] but not with precisely our hypothesis or with a global analysis of relevant data including radiative corrections.

The neutrinos of the first two generations are directly involved in νq and $\nu_\mu e$ data, and they and ν_τ are involved in $\Gamma_Z^{\rm inv}$ and $\Gamma(\tau\rightarrow e,\mu)$. We analyze these data and in addition we will use present world averages for eq, M_W, Γ^l, and $\Gamma^{\rm had}$ (see Table I for the explicit values).[1,2] We assume universality except for neutrino mixing. We obtain the experimental value of $\Gamma(\tau\rightarrow e,\mu)$ as the product $\Gamma(\tau)B(\tau\rightarrow e,\mu)$, adding the errors in quadrature.[1] Other τ decays behave similarly to the semileptonic ones, but with further experimental and theoretical complications (which we omit here[6]). For universal (ν_τ) mixing the necessary one-loop expressions to fit the former data are those of the MSM but with the electroweak couplings for $\nu_{(\tau)}$ reduced by $\cos^2\epsilon_{(\tau)}$ for neutral interactions and by $\cos\epsilon_{(\tau)}$ for charged interactions.[5,6] This is because the massless neutrino states become [after diagonalizing $\mathcal{M}$ in Eq. (1)]

$$\nu_{(\tau)}=\cos\epsilon_{(\tau)}\,\nu_{(\tau)L}-\sin\epsilon_{(\tau)}N_{(\tau)}\,. \qquad (2)$$

Then, as N's do not couple to any MSM particle, the $\nu_{(\tau)}$ couplings result from replacing $\nu_{(\tau)L}$ [after inverting Eq. (2)] by $\cos\epsilon_{(\tau)}\nu_{(\tau)}$ in the MSM Lagrangian. We use the on-shell scheme with α, G_μ, and M_Z fixed to their central experimental values,[1] and m_t, m_H, and $\sin\epsilon_{(\tau)}$ as free parameters ($\sin^2\theta_W\equiv 1-M_W^2/M_Z^2$).[6,9]

Table I shows results from a global χ^2 fit. Data are from Ref. 1, except for $\Gamma_Z^{{\rm inv},l,{\rm had}}$ from Ref. 2. We specify in parenthesis the contributions to the total χ^2 of the different data sets. We also give, for the best fit, the values of the different quantities. The total χ^2 and the central values for the free parameters $m_{t,H}$ and $\sin\epsilon_{(\tau)}$ for universal ν (ν_τ) mixing are also presented in Table I. In Fig. 1 we show the minimal χ^2 as a function of $\sin\epsilon_{(\tau)}$. The inclusion of M_Z in the χ^2 fit results in variations of 0.4% and leaves everything essentially unchanged. (The preferred M_Z value is in this case 91.168 GeV, to be compared to 91.161±0.031 GeV.[1]) This justifies presenting fits with $M_Z=91.161$ GeV.

If the model we were comparing with the data were well established, or unusually well motivated, the results of Table I and Fig. 1 could be interpreted as favoring a value of $\sin\epsilon_{(\tau)}$ different from zero, in which case there would be evidence that ν_τ, or all three light neutrinos, were mixing with heavy fermions. The heavy fermions are totally neutral with respect to standard-model charges, so they only appear in particle-physics data via their mixing with the light neutrinos. Although the new heavy fermions do not couple to Z,W, they can be pro-

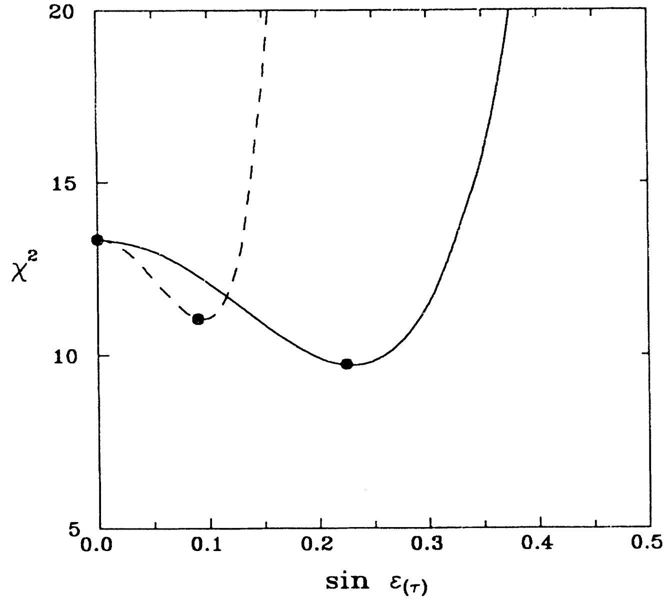

FIG. 1. Minimum χ^2 as a function of the $\nu_{(\tau)}$ mixing for the cases of universal ν (dashed) and ν_τ (solid) mixing. The dots correspond to the minima for no mixing ($\sin\epsilon_{(\tau)}=0$, $\chi^2/\text{DOF}=13.35/13$), universal ν mixing ($\sin\epsilon=0.09$, $\chi^2/\text{DOF}=11.05/12$), and ν_τ mixing ($\sin\epsilon_\tau=0.22$, $\chi^2/\text{DOF}=9.74/12$).

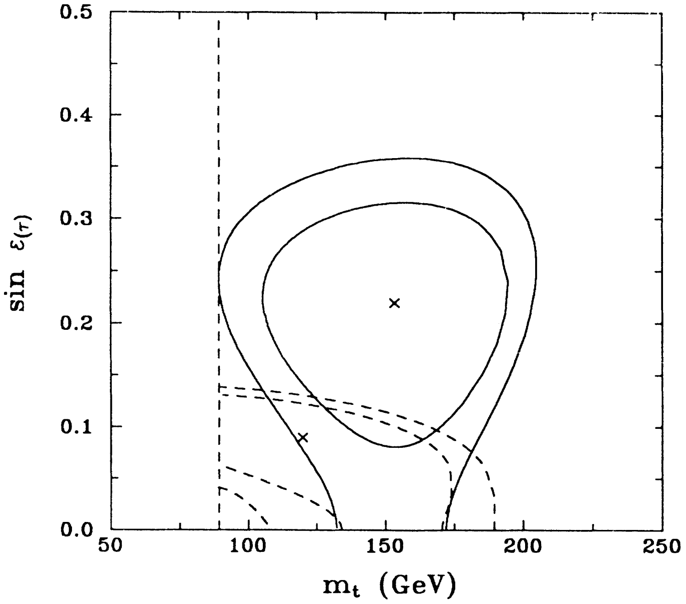

FIG. 2. $\sin\epsilon_{(\tau)}$-m_t (GeV) plane: The minima for universal ν mixing (0.09,120) and ν_τ mixing (0.22,153) are depicted by crosses. We also show the 90%-C.L. ($\Delta\chi^2=4.61$) and 75%-C.L. ($\Delta\chi^2=2.77$) contours for universal ν (dashed) and ν_τ (solid) mixing. The vertical (dashed) line corresponds to the present experimental limit, $m_t > 89$ GeV.

duced at accelerators by the mixing if they are not too heavy, e.g., $e^+e^- \to Z \to \nu_{(\tau)}+N_{(\tau)}$.[10] Depending on whether and how they decay, which will be analyzed in later work, they may be detectable under some circumstances, e.g., as new long-lived particles.

The pieces of data favoring the mixing are those involving ν_τ, Γ_Z^{inv} and $\Gamma(\tau\to e,\mu)$. The remaining data, in particular νq and $\nu_\mu e$, do not prefer or contradict neutrino mixing. A larger mixing for ν_τ than for $\nu_{e,\mu}$ is reasonable if the ν_l mixing happens to be proportional to a power of m_l. In a sense our point in this paper is that two pieces of data slightly suggest this mixing, and no other relevant data oppose it, so we encourage people to take the mixing idea seriously.

In Fig. 2 we show the implications for m_t of a $\nu_{(\tau)}$ mixing. Observing the last three columns in Table I we see that the improvement in the χ^2 for the case of universal ν mixing is mainly due to the better fit of Γ_Z^{inv} and Γ_Z^{had}. This is possible because the combined action of the mixing and the m_t dependence can accommodate both without upsetting the other data. On the other hand, the ν_τ mixing can improve Γ_Z^{inv} but the unmixed neutrinos of the first two generations prevent, through the other experimental inputs (in particular G_μ), m_t from helping to improve Γ_Z^{had}. In the latter case, $\Gamma(\tau\to e,\mu)$ can be nicely fitted. At this stage it is obvious that the possibility of new physics weakens considerably the top-mass predictions. In fact, in the MSM any new precise measurement (apart from α, G_μ, and M_Z), for instance that of M_W, sensitive to m_t, will be a determination of the top mass.[11]

Concerning other physics, $\beta\beta$ decay is unaffected because the mass matrix $\mathcal{M}$ in Eq. (1) does not lead to lepton-number violation.[12] In our model the three light neutrinos are massless (and the heavy ones very massive, typically of the order of M_W or higher), so no effects show up in nuclear β decay.[13] For the same reason, and due to the fact that electroweak processes relevant to nucleosynthesis calculations involve essentially experimental data, the ^{4}He abundance should be the same as in the MSM scenario. Moreover, as the ν mixing is with a very heavy neutrino, it is of no relevance for the solar-neutrino problem.[14] In summary, no new contributions to cosmology seem to result from this standard-model extension, except maybe for small contributions to the density of the Universe and to the cosmic microwave and neutrino backgrounds resulting from the final products of the heavy neutrino decay.[15] Finally, it is interesting to note that better data on the τ lifetime and on (e.g., from a τ factory) $B(\tau\to e,\mu)$, and further LEP data, will either strengthen the notion that the light neutrinos are mixing with heavy neutral ones or reject it.

We close by remarking that we have used the model described by Eq. (1) as a testing bench to look for evidence of neutrino mixing. Since the model predicted that the τ lifetime was a little longer, and Γ_Z^{inv} a little less, than their MSM values (and the data hint at both) we have done an analysis showing that such a model can give effects of the relevant size without being inconsistent with any other precision measurements. We hope that the current weakness of the effects in the data will not cause anyone to take the basic idea less seriously.

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