The Tau Neutrino as the Lightest Supersymmetric Particle

\( \nu_\tau = \text{LSP} \)

Ernest Ma

Department of Physics, University of California, Riverside, CA 92521

and

Department of Physics, University of Wisconsin, Madison, WI 53706

Abstract

Given the conservation of baryon number as well as electron and muon numbers, all present data can be explained without the need of a conserved quantum number for the tau lepton and its neutrino. A supersymmetric extension of the standard model naturally allows for such a scenario. One consequence is that the tau neutrino becomes the lightest supersymmetric particle.

To appear in Proceedings of the Second Talinn Neutrino Symposium.
1. Introduction

It is usually thought that present experimental data indicate that baryon number (B), electron number (L_e), muon number (L_µ), and tau number (L_τ) should be taken as conserved quantum numbers, at least to a very good approximation. Actually, if we assume the conservation of B, L_e, and L_µ, then there is no need for L_τ. For example, the fact that in neutrino interactions on nuclei, τ leptons are not produced is explained by the conservation of L_e and L_µ. Analogously, the fact that τ does not decay into an antiproton + mesons requires only the conservation of B.

The reason that L_τ appears to be conserved is that given the standard SU(2) × U(1) electroweak gauge model with its minimal particle content, the conservation of B, L_e, L_µ, and L_τ is automatic. An excursion beyond the standard model is necessary to see how L_τ may be different from L_e and L_µ.

2. Supersymmetric Standard Model

Consider for example any supersymmetric extension of the standard model. In a notation where only left chiral superfields are counted, the quarks and leptons transform under SU(3) × SU(2) × U(1) as follows:

\[
Q \equiv (u, d)_L \sim (3, 2, 1/6), \quad u^c \sim (\overline{3}, 1, -2/3), \quad d^c \sim (\overline{3}, 1, 1/3), \quad (1)
\]

\[
L \sim (\nu, \ell)_L \sim (1, 2, -1/2), \quad \ell^c \sim (1, 1, 1). \quad (2)
\]

The Higgs superfields are

\[
\Phi_1 \sim (1, 2, -1/2), \quad \Phi_2 \sim (1, 2, 1/2). \quad (3)
\]

The allowed terms in the superpotential are then

\[
\Phi_1 \Phi_2, \quad \Phi_1 Q_i d^c_j, \quad \Phi_2 Q_i u^c_j, \quad \Phi_1 L_i \ell^c_i;
\]
and

\[ L_i \Phi_2, \quad L_i Q_j d_k^c, \quad L_i L_j \ell_k^c, \quad u_i^c d_j^c d_k^c. \]

Whereas the first four terms conserve B, L^e, L^\mu, and L^\tau, the above four do not and they are usually just ignored. What this amounts to is the imposition of B, L^e, L^\mu, and L^\tau as conserved quantum numbers.

Instead of forbidding all possible combinations of the last four terms, it is just as natural to forbid some of them, resulting in the conservation of one or two lepton numbers. It has been shown\cite{1} that there are 5 \times 3 ways of doing this, as given below.

| Model | e   | \mu | \tau         |
|-------|-----|-----|--------------|
| 1     | (1,0) | (0,1) | (0,0)       |
| 2     | (1,0) | (0,1) | (1,1)       |
| 3     | 1    | -1   | 0           |
| 4     | 1    | 1    | 0           |
| 5     | 1    | 0    | 0           |

Here the lepton-number assignments (L^e, L^\mu) are displayed for models 1 and 2, and L for models 3-5. For each model, there are of course three possible variations resulting from the permutations of e, \mu, and \tau.

### 3. Zero Lepton Number for \( \tau \)

If \( \tau \) is to have zero lepton number, then Model 1 is the prototype.\cite{2} The superpotential is given by

\[
W = \mu \Phi_1 \Phi_2 + h_i \Phi_1 L_i \ell_1^c + h_i^u \Phi_2 Q_i u_j^c + h_i^d \Phi_1 Q_i d_j^c + \mu' L_3 \Phi_2 + f_e L_3 L_1 \ell_1^c + f_\mu L_3 L_2 \ell_2^c + f_{ij} L_3 Q_i d_j^c,
\]
where the coupling matrix $h_i$ has been chosen to be diagonal. It reduces to the conventional supersymmetric model in the limit $f_e$, $f_\mu$, $f_{ij}$, and $\mu'$ go to zero. The neutralino mass matrix spanning the gauginos ($-i\lambda_\gamma, -i\lambda_z$), the higgsinos ($\psi_1^0, \psi_2^0$), and $\nu_3$ is then

$$M = \begin{pmatrix}
c^2 M_1 + s^2 M_2 & sc(M_2 - M_1) & 0 & 0 & 0 \\
s c(M_2 - M_1) & s^2 M_1 + c^2 M_2 & M_Z \cos \beta & -M_Z \sin \beta & 0 \\
0 & M_Z \cos \beta & 0 & -\mu & 0 \\
0 & -M_Z \sin \beta & -\mu & 0 & -\mu' \\
0 & 0 & 0 & -\mu' & 0
\end{pmatrix}, \quad (5)$$

where $c \equiv \cos \theta_W$, $s \equiv \sin \theta_W$, $\tan \beta \equiv v_2/v_1 = \langle \phi_2^0 \rangle/\langle \phi_1^0 \rangle$, and $M_{1,2}$ are allowed gauge-invariant mass terms for the U(1) and SU(2) gauginos. As a result, the physical $\nu_\tau$ is mostly $\nu_3$, but there is a small admixture of the other states so that it acquires a small see-saw Majorana mass

$$m_{\nu_\tau} \sim \frac{\mu'^2}{2\mu \tan \beta}. \quad (6)$$

For $\mu \sim 1$ TeV, $\tan \beta \sim 10$, $\mu' \sim 10$ MeV, an interesting value of $5$ eV is obtained for $m_{\nu_\tau}$.

In the conventional supersymmetric model without the $\mu'$ term, the smallest eigenvalue of the $4 \times 4$ neutralino mass matrix is that of the lightest supersymmetric particle (LSP) and since R parity, defined to be $(-1)^{2j+3B+L}$, is conserved in that case, the LSP is absolutely stable. This has very important implications for the experimental search for supersymmetry because the LSP would be a weakly interacting particle which leaves the detector unobserved except that it carries away momentum and energy. Here, it is clear that $\nu_\tau$ is the LSP, so that any of the other neutralinos such as the photino $\tilde{\gamma}$ (i.e. $-i\lambda_\gamma$) would decay through a scalar electron for example into $e^+e^-\nu_\tau$ and might not remain stable within the detector in a typical high-energy physics experiment.
4. Phenomenological Constraints and Implications

The existence of the $L_3 Q_i d_j^c$ term is a source of tree-level flavor-changing neutral currents. The most stringent constraints come from the neutral kaons. The magnitude of the $K_L - K_S$ mass difference implies

$$|f_{sd} f_{ds}^*|^\frac{1}{2} < 10^{-4} \left( \frac{m_{\tilde{\nu}_\tau}}{100 \text{ GeV}} \right), \quad (7)$$

and the $K_L \to \mu^+ \mu^-$ rate implies

$$|f_\mu|^\frac{1}{2} \left( |f_{sd}|^2 + |f_{ds}|^2 \right)^{\frac{1}{4}} < 5 \times 10^{-4} \left( \frac{m_{\tilde{\nu}_\tau}}{100 \text{ GeV}} \right). \quad (8)$$

The possible deviation from zero of the Michel parameter $\eta$ in $\mu \to e \nu \bar{\nu}$ decay implies

$$|\text{Re} f_\mu f_e^*|^\frac{1}{2} < 0.11 \left( \frac{m_{\tilde{\nu}_\tau}}{100 \text{ GeV}} \right), \quad (9)$$

The parameters $\rho$ and $\delta$ remain at 0.75 as in the standard model.

Since the nonconservation of $L^\tau$ is only achieved here with the intervention of supersymmetry, possible tests of this model will likely involve the direct production of supersymmetric particles. The best case is

$$p \bar{p} \ (\text{or} \ pp) \to \tau^+ \tau^- + 2 \text{ quark jets},$$

which involves (for the $\tau^+ \tau^+$ mode) the subprocesses $u \bar{d} \to \tilde{u}_L \tilde{d}_R^* \sigma \text{ through gluino exchange}$ and their subsequent decay into $d \tau^+$ and $\bar{u} \tau^+$ respectively. The analogous reaction for an electron-proton collider is

$$e p \to \tau^- \tau^+ + 1 \text{ quark jet} + \text{missing energy},$$

which proceeds via the production of $\tilde{e}_R \tilde{d}_R^*$ and their subsequent decay into $\nu_e \tau^-$ and $u \tau^-$ respectively.
5. Conclusion

If supersymmetry exists, the issue of lepton number conservation will have to be reexamined experimentally. The conventional wisdom that L is conserved additively (or multiplicatively if neutrinos have Majorana masses) may not be correct. An interesting possibility would be that $\tau$ is actually a nonleptonic superparticle and

$$\nu_\tau = \text{LSP}$$

ACKNOWLEDGEMENT

I thank Professors Ots and Tammelo for their great hospitality and a very stimulating meeting. This work was supported in part by the U.S. Department of Energy under Contract No. DE-AT03-87ER40327.

References

[1] E. Ma and D. Ng, Phys. Rev. D41, 1005 (1990).

[2] E. Ma and P. Roy, Phy. Rev. D41, 988 (1990).