Verifiable Origin of Neutrino Mass at TeV Scale

Ernest Ma

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

Abstract

The physics responsible for neutrino mass may reside at or below the TeV energy scale. The neutrino mass matrix in the \((\nu_e, \nu_\mu, \nu_\tau)\) basis may then be deduced from future high-energy accelerator experiments. The newly observed excess in the muon anomalous magnetic moment may also be related.

Talk given at the 7th International Workshop on Topics in Astroparticle and Underground Physics, Assergi, Italy (September 8-12, 2001)
1 Introduction

The conventional wisdom in neutrino physics is that the origin of neutrino mass is at a very high energy scale, say $10^{13}$ GeV or greater, in which case there is no hope of verification experimentally. On the other hand, recent papers [1, 2, 3] have shown that it is just as natural to have the origin of neutrino mass at the TeV scale and be amenable to direct experimental verification.

In the minimal Standard Model with one Higgs doublet $\Phi = (\phi^+, \phi^0)$ and 3 lepton doublets $L = (\nu, l)_L$ and singlets $l_R$ only, neutrino mass must come from the effective dimension-5 operator [4, 5]

$$\frac{1}{\Lambda} L L \Phi \Phi = \frac{1}{\Lambda} (\nu \phi^0 - l \phi^+)^2, \quad (1)$$

which shows that the form of $m_\nu$ must necessarily be “seesaw”, i.e. $v^2/\Lambda$ where $v = \langle \phi^0 \rangle$, whatever the underlying mechanism for neutrino mass is.

The canonical seesaw mechanism [6] assumes 3 heavy right-handed singlet lepton fields $N_R$ with the Yukawa couplings $f L N \Phi$ and the Majorana mass $m_N$, hence Eq.(1) is realized with the famous expression

$$m_\nu = \frac{f^2 v^2}{m_N}. \quad (2)$$

Note that lepton number is violated by $m_N$ in the denominator and it should be large for a small neutrino mass, i.e.

$$m_\nu \sim \left( \frac{f}{1.0} \right)^2 \left( \frac{10^{13} \text{ GeV}}{m_N} \right) \text{eV}. \quad (3)$$
2 Higgs Triplet Model

An equally satisfactory realization of Eq. (1) is to use a Higgs triplet $\xi = (\xi^{++}, \xi^+, \xi^0)$ with

$$
\mathcal{L}_{\text{int}} = f_{ij} [\xi^0 \nu_i \nu_j + \xi^+(\nu_i l_j + l_i \nu_j)/\sqrt{2} + \xi^{++} l_i l_j] \\
+ \mu (\bar{\xi}^0 \phi^0 \phi^0 - \sqrt{2} \xi^+ \phi^0 + \xi^- \phi^+ + \xi^- \phi^+) + H.c.
$$

This model violates lepton number explicitly, but if the parameter $\mu$ is set to zero, it becomes the Gelmini-Roncadelli model [9], which is now experimentally ruled out. On the other hand, with $\mu \neq 0$ and $m_\xi^2$ positive and large, i.e. $m_\xi >> v$, we have instead [8]

$$
m_\nu = \frac{2 f_{ij} \mu v^2}{m_\xi^2} = 2 f_{ij} \langle \xi^0 \rangle.
$$

Note that the effective operator of Eq. (1) is realized here with a simple rearrangement of the individual terms, i.e.

$$
L_i L_j \Phi \Phi = \nu_i \nu_j \phi^0 \phi^0 - (\nu_i l_j + l_i \nu_j) \phi^+ \phi^0 + l_i l_j \phi^+ \phi^+.
$$

Note also that lepton number is violated in the numerator in this case. If $f_{ij} \sim 1$, then $\mu/m_\xi^2 < 10^{-13}$ GeV$^{-1}$. Hence $m_\xi \sim 1$ TeV is possible, if $\mu < 100$ eV. To obtain such a small mass parameter, the “shining” mechanism of extra large dimensions [10] may be used. In that case, the doubly charged $\xi^{\pm \pm}$ can be easily produced at colliders and $\xi^{++} \rightarrow l_i^+ l_j^+$ is a distinct and backgroundless decay which maps out $|f_{ij}|$, and thus determine directly the neutrino mass matrix of Eq. (5) up to an overall scale. [1] This model also predicts observable $\mu - e$ conversion in nuclei within the sensitivity of proposed future experiments.

3 Leptonic Higgs Doublet Model

Another simple and interesting way to have the origin of neutrino mass at the TeV scale has recently been proposed [4]. As in the canonical seesaw model, we have again $3 N_R$’s but they
are now assigned $L = 0$ instead of the customary $L = 1$. Hence the Majorana mass terms are allowed but the usual $LN\Phi$ terms are forbidden by lepton-number conservation. The $LL\Phi\Phi$ operator of Eq.(1) is not possible and $m_\nu = 0$ at this point.

We now add a new scalar doublet $\eta = (\eta^+, \eta^0)$ with $L = -1$, then $fLN\eta$ is allowed, and the operator $LL\eta\eta$ will generate a nonzero neutrino mass if $\langle \eta^0 \rangle \neq 0$. The trick now is to show how $f\langle \eta^0 \rangle < 1$ MeV can be obtained naturally, so that $m_N \sim 1$ TeV becomes possible and amenable to experimental verification, in contrast to the very heavy $N_R$’s of the canonical seesaw mechanism.

Consider the following Higgs potential:

$$V = m_1^2 \Phi^\dagger \Phi + m_2^2 \eta^\dagger \eta + \frac{1}{2} \lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2} \lambda_2 (\eta^\dagger \eta)^2$$

$$+ \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta) (\eta^\dagger \Phi) + \mu_{12}^2 (\Phi^\dagger \eta + \eta^\dagger \Phi),$$

(7)

where the $\mu_{12}^2$ term breaks lepton number softly and is the only possible such term. Let $\langle \phi^0 \rangle = v$, $\langle \eta^0 \rangle = u$, then the equations of constraint for the minimum of $V$ are given by

$$v[m_1^2 + \lambda_1 v^2 + (\lambda_3 + \lambda_4)u^2] + \mu_{12}^2 u = 0,$$  

(8)

$$u[m_2^2 + \lambda_2 u^2 + (\lambda_3 + \lambda_4)v^2] + \mu_{12}^2 v = 0.$$  

(9)

Consider the case $m_1^2 < 0$, $m_2^2 > 0$, and $|\mu_{12}^2| << m_2^2$, then

$$v^2 \simeq -\frac{m_1^2}{\lambda_1}, \quad u \simeq -\frac{\mu_{12}^2 v}{m_2^2 + (\lambda_3 + \lambda_4)v^2}.$$  

(10)

Hence $u$ may be very small compared to $v(= 174$ GeV). For example, if $m_2 \sim 1$ TeV, $|\mu_{12}^2| \sim 10$ GeV$^2$, then $u \sim 1$ MeV and

$$m_\nu \sim \left( \frac{f}{1.0} \right)^2 \left( \frac{1 \text{ TeV}}{m_N} \right) \text{ eV}.$$  

(11)

Since both $m_N$ and $m_2$ are now of order 1 TeV, they may be produced at future colliders and be detected. (I) If $m_2 > m_N$, then the physical charged Higgs boson $h^+$, which is mostly
$\eta^+$, will decay into $N$, which then decays into a charged lepton and a $W$ boson via $\nu - N$ mixing:

$$h^+ \rightarrow l_i^+ N_j, \quad N_j \rightarrow l_k^+ W^\mp.$$  \hspace{1cm} (12)

(II) If $m_N > m_2$, then

$$N_i \rightarrow l_j^+ h^\mp, \quad h^+ \rightarrow t\bar{b},$$  \hspace{1cm} (13)

the latter coming from $\Phi - \eta$ mixing. In either case, $m_2$ and $m_N$ can be determined kinematically, and $|f_{ij}|$ measured up to an overall scale.

In summary, the particle spectrum of the leptonic Higgs doublet model consists of the usual Standard-Model particles, including the one physical Higgs boson $h_1^0$, 3 heavy $N_R$'s at the TeV scale, and a heavy scalar doublet $(h^\pm, h_2^0, A)$ of individual masses $\sim m_2$. The charged Higgs boson $h^\pm$ can be pair-produced at hadron colliders, whereas $N_R (h^\pm)$ can be produced at lepton colliders via the exchange of $h^\pm (N_R)$.

## 4 The Size of Lepton Number Violation

It has been shown in the above that whereas Majorana neutrino masses have to be tiny, the actual magnitude of lepton number violation may come in all sizes.

1. **Large**: $m_N \sim 10^{13}$ GeV in the canonical seesaw mechanism.

2. **Medium**: $|\mu_{12}^2| \sim 10$ GeV$^2$ in the leptonic Higgs doublet model with $m_N \sim 1$ TeV.

3. **Small**: $\mu \sim 10$ eV in the Higgs triplet model ($m_\xi \sim 1$ TeV) with a singlet bulk scalar in extra large dimensions.

In (2) and (3), direct experimental determination of the relative magnitudes of the elements of $M_\nu$ is possible at future colliders.
5 Muon Anomalous Magnetic Moment

The recent measurement \[11\] of the muon anomalous magnetic moment appears to disagree with the Standard-Model prediction \[12\] by 2.6σ, i.e.

\[
\Delta a_{\mu} = a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} > 215 \times 10^{-11}
\]

at 90% confidence level. The origin of this discrepancy may be directly related to the TeV physics responsible for neutrino mass. If the leptonic Higgs doublet model \[2\] is combined with a similar model of quark masses \[13\] to become a supersymmetric model \[14\] with 4 Higgs doublets, then the loop contribution of $\tilde{N}$ and $\tilde{h}^+$ will in general cause the transition $l_i \rightarrow l_j \gamma$. Hence there are predictions \[3\] for the muon anomalous magnetic moment as well as lepton flavor violating processes such as $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, etc.

If the neutrino mass matrix is hierarchical, then Eq. (14) implies $B(\tau \rightarrow \mu\gamma) > 8.0 \times 10^{-6}$, which contradicts the experimental upper bound of $1.1 \times 10^{-6}$. To avoid this restriction, the neutrino mass matrix has to be nearly degenerate, in which case we have the interesting prediction of

\[
\frac{\Gamma(\mu \rightarrow e\gamma)}{m_{\mu}^5} : \frac{\Gamma(\tau \rightarrow e\gamma)}{m_{\tau}^5} : \frac{\Gamma(\tau \rightarrow \mu\gamma)}{m_{\tau}^5} = \frac{1}{2}(\Delta m^2)_{\text{sol}}^2 : (\Delta m^2)_{\text{atm}}^2 : (\Delta m^2)_{\text{atm}}^2,
\]

where bimaximal mixing has been assumed.

In Fig. (1), the branching fractions of $\tau \rightarrow \mu\gamma$ and $\mu \rightarrow e\gamma$, and the $\mu - e$ conversion ratio in $^{13}$Al are plotted using the lower bound of Eq. (14), as a function of the common neutrino mass $m_{\nu}$. The values

\[
(\Delta m^2)_{\text{atm}} = 3 \times 10^{-3} \text{ eV}^2, \quad (\Delta m^2)_{\text{sol}} = 3 \times 10^{-5} \text{ eV}^2,
\]

have been chosen according to present data from neutrino-oscillation experiments. At $m_{\nu} \approx 0.2$ eV, which is in the range of present upper limits on $m_{\nu}$ from neutrinoless double beta
decay, $B(\mu \to e\gamma)$ and $R_{\mu e}$ are both at their present experimental upper limits. Hence Eq. (15) will be tested in new experiments planned for the near future which will lower these upper limits.

6 Conclusion

Physics at the TeV scale may reveal the true origin of neutrino mass, so that accelerator experiments will become complementary to nonaccelerator experiments in determining the neutrino mass matrix without ambiguity.

7 Acknowledgements

This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837.

8 Afterword

This talk was being given in Assergi, Italy on September 11, 2001, at the moment the infernal attack on the World Trade Center in New York began. All of humanity is the victim today and for years to come.

References

[1] E. Ma, M. Raidal, and U. Sarkar, Phys. Rev. Lett. 85, 3769 (2000); [hep-ph/0012101](http://arxiv.org/abs/hep-ph/0012101) (Nucl. Phys. B, in press).

[2] E. Ma, Phys. Rev. Lett. 86, 2502 (2001).
[3] E. Ma and M. Raidal, Phys. Rev. Lett. 87, 011802 (2001); Z.-Z. Xing, Phys. Rev. D64, 017304 (2001).

[4] S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979).

[5] E. Ma, Phys. Rev. Lett. 81, 1171 (1998).

[6] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Z. Freedman (North-Holland, Amsterdam, 1979), p. 315; T. Yanagida, in *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe*, edited by O. Sawada and A. Sugamoto (KEK, Tsukuba, Japan, 1979), p. 95; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980).

[7] J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980).

[8] E. Ma and U. Sarkar, Phys. Rev. Lett. 80, 5716 (1998).

[9] G. B. Gelmini and M. Roncadelli, Phys. Lett. B99, 411 (1981).

[10] N. Arkani-Hamed and S. Dimopoulos, hep-ph/9811353.

[11] H. N. Brown *et al.*, Phys. Rev. Lett. 86, 2227 (2001).

[12] A. Czarnecki and W. J. Marciano, Phys. Rev. D64, 013014 (2001); other estimates of the possible discrepancy include J. Erler and M. Luo, Phys. Rev. Lett. 87, 071804 (2001); F. J. Yndurain, hep-ph/0102312; S. Narison, Phys. Lett. B513, 53 (2001); F. Jegerlehner, hep-ph/0104304; K. Melnikov, hep-ph/0105267.

[13] E. Ma, Phys. Lett. B516, 165 (2001).

[14] E. Ma, hep-ph/0107177 (Phys. Rev. D64, in press).
Doublet model

Figure 1: Lower bounds on $B(\tau \rightarrow \mu \gamma)$, $B(\mu \rightarrow e \gamma)$, and $R_{\mu e}$. 