PROCEEDINGS OF SCIENCE

Horizontal Symmetry and Large Neutrino Magnetic Moments

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We investigate new symmetries which decouple the mass from the magnetic moment of neutrinos and their theoretical and phenomenological implications are discussed. Our proposed model is based on $SU(2)_H$ horizontal symmetry that can generate large neutrino transition magnetic moment without inducing unacceptably large neutrino masses. In the $SU(2)_H$ symmetric limit, the transition magnetic moment is nonzero, while the neutrino mass vanishes. The simplification we suggest is based on the symmetry being approximate, which we also generalize to a three-family $SU(3)_H$-symmetry. We have also investigated a spin symmetry mechanism that can generate large μ_ν while keeping m_ν small. This talk is based on results obtained with K.S. Babu, and Manfred Lindner and presented in hep-ph 2007.04291 [1].

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Observations of sunspot activity in the late 1980s and early 1990s [2, 3] sparked interest in neutrino magnetic moments, which had been studied for seven decades [4], prior to the discovery of the neutrino. Later, several studies investigated neutrino magnetic moments in more detail [5–13]. There is a growing interest in studying neutrino magnetic moments because they have the potential to solve many unsolved mysteries, such as the excess of electron recoil events at XENON1T [14], the ANITA anomalous events [15, 16], the long-standing MiniBooNE [17] and muon $g-2$ anomalies [18, 19]. Strong bounds on neutrino magnetic moment can arise from astrophysical setups as well [20–23]. The presence of a non-zero neutrino magnetic moment allows for a direct coupling between neutrinos and photons, thereby allowing for neutrino radiative decays, as well as plasmon decays to neutrino-antineutrino pairs. The strongest bounds usually arise from globular cluster stars, where plasmon decay can delay helium ignition, leading to anomalous cooling of stars. Absence of any such observational evidence leads to $\mu_\nu \leq 3\times 10^{-12}\mu_B$ [24]. For an updated bound, check [25]. However, it has been recently pointed out that this astrophysical limit can be relaxed by considering "neutrino trapping mechanism" [1, 19]. From a theoretical standpoint, the anticipated magnetic moments of neutrinos are imperceptibly tiny in many neutrino mass models that generate the known neutrino masses and mixings [26, 27]; for a summary, see Ref. [28]. However, it is conceivable to construct theories consistent with neutrino mass generation that have a quite large neutrino magnetic moments [1]. Thus, understanding the neutrino magnetic moment may give valuable insight into the process by which neutrinos acquire mass and other characteristics.

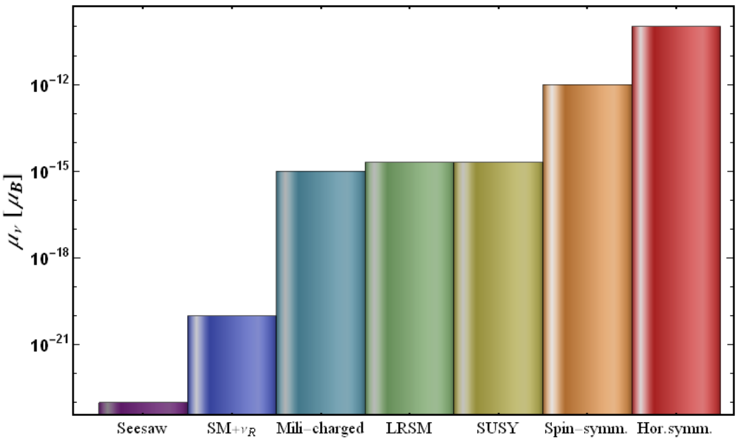

Figure 1: Theoretical predictions of the neutrino magnetic moments in different neutrino mass models. For details, see Ref. [1].

We present a simplified model for large transition magnetic moment $\mu_{\nu_e\nu_\mu}$ based on an *approximate* $SU(2)_H$ horizontal symmetry acting on the electron and the muon families. Our simplification is that the symmetry is only approximate, broken explicitly by electron and muon masses. Fewer new particles would then suffice to complete the model. The explicit breaking of $SU(2)_H$ by the lepton masses is analogous to chiral symmetry breaking in the strong interaction sector by masses of the light quarks. Such breaking will have to be included in the neutrino sector as well. We have computed the one-loop corrections to the neutrino mass from these explicit breaking terms and found them to small enough so as to not upset the large magnetic moment solution.

The only violation of $SU(2)_H$ acting on the electron and muon fields arises from their unequal masses. This mass splitting, normalized to the weak scale, is indeed a small parameter: $(m_\mu^2 - m_e^2)/m_W^2 = 1.7\times 10^{-6}$. Violation of $SU(2)_H$ symmetry in the neutrino masses can be of this order, which suggests that large $\mu_{\nu_e\nu_\mu}$ can be realized without inducing large m_ν. In fact, the effect of the $SU(2)_H$ breaking parameter $(m_\mu^2 - m_e^2)/m_W^2$ in the neutrino sector will be accompanied by a loop suppression factor of order 10^{-2}, which would make m_ν even smaller. Our model is a simple extension of the Zee model of neutrino mass that accommodates an $SU(2)_H$ symmetry. The Zee model is one of the simplest models of neutrino mass generation with new scalars possibly having masses in the TeV scale. A sizable neutrino transition magnetic moment requires such particles, along with violation of lepton number.

The gauge symmetry of the model is $SU(3)_c \times SU(2)_L \times U(1)_Y$, with no new fermions added to the Standard Model. In addition, there is an approximate $SU(2)_H$ symmetry. Leptons of the Standard Model transform under $SU(2)_L \times U(1)_Y \times SU(2)_H$ as follows:

$$\begin{aligned}
\psi_L &= \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L \qquad (2, -\frac{1}{2}, 2) \\
\psi_R &= (e \quad \mu)_R \qquad (1, -1, 2) \\
\psi_{3L} &= \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad (2, -\frac{1}{2}, 1) \\
& \tau_R \qquad (1, -1, 1)\ .
\end{aligned} \tag{1}$$

Here $SU(2)_H$ acts horizontally, while $SU(2)_L$ acts vertically. The first two families of leptons form a doublet of $SU(2)_H$ while the τ family is a singlet. All quark fields are assumed to be $SU(2)_H$ singlets.

The Higgs sector of the model consists of the following multiplets:

$$\begin{aligned}
\phi_S &= \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} \qquad \left(2, \tfrac{1}{2}, 1\right) \\
\Phi &= \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} \qquad \left(2, \tfrac{1}{2}, 2\right) \\
\eta &= (\eta_1^+ \quad \eta_2^+) \qquad (1, 1, 2)\ .
\end{aligned} \tag{2}$$

The ϕ_S filed is the Standard Model Higgs doublet, which has its usual Yukawa couplings with the quarks. The ϕ_S field is also responsible for electroweak symmetry breaking. The vacuum expectation values (VEV) of ϕ_S^0 is denoted as $\langle \phi_S^0 \rangle = v/\sqrt{2}$ where $v \simeq 246$ GeV. The ϕ fields are assumed to acquire no VEVs. This is a consistent assumption, which is valid even after the explicit breaking of $SU(2)_H$ symmetry.

Under $SU(2)_L \times SU(2)_H$, the transformation of various fields is as follows:

$$\begin{aligned}
\psi_L \to U_L \psi_L U_H^T, \quad \psi_{\tau L} \to U_L \psi_{\tau L}, \quad \psi_R \to \psi_R U_H^T \\
\phi_S \to U_L \phi_S, \quad \Phi \to U_L \Phi U_H^T, \quad \eta \to \eta U_H^T\ .
\end{aligned} \tag{3}$$

Here U_L and U_H are unitary matrices associated with $SU(2)_L$ and $SU(2)_H$ transformations. The Yukawa Lagrangian in the lepton sector that is invariant under the gauge symmetry as well as

$SU(2)_H$ is then

$$\begin{aligned}\mathcal{L}_{\rm Yuk} \;=\;& h_1\,{\rm Tr}\left(\bar{\psi}_L\phi_S\psi_R\right) + h_2\bar{\psi}_{3L}\phi_S\tau_R + h_3\bar{\psi}_{3L}\Phi i\tau_2\psi_R^T \\ & f\eta\tau_2\psi_L^T\tau_2 C\psi_{3L} + f'\,{\rm Tr}\left(\bar{\psi}_L\Phi\right)\tau_R + H.c. \end{aligned} \tag{4}$$

Expanded in component form, this reads as:

$$\begin{aligned}\mathcal{L}_{\rm Yuk} \;=\;& h_1\left[(\bar{\nu}_e e_R\phi_S^+ + \bar{e}_L e_R\phi_S^0) + (\bar{\nu}_\mu \mu_R\phi_S^+ + \bar{\mu}_L\mu_R\phi_S^0)\right] + h_2\left[\bar{\nu}_\tau\tau_R\phi_S^+ + \bar{\tau}_L\tau_R\phi_S^0\right] \\ +\;& h_3\left[-(\bar{\nu}_\tau e_R\phi_2^+ + \bar{\tau}_L e_R\phi_2^0) + (\bar{\nu}_\tau\mu_R\phi_1^+ + \bar{\tau}_L\mu_R\phi_1^0)\right] \\ +\;& f\left[\left(\nu_e^T C\tau_L - e_L^T C\nu_\tau\right)\eta_2^+ - \left(\nu_\mu^T C\tau_L - \mu_L^T C\nu_\tau\right)\eta_1^+\right] \\ +\;& f'\left[(\bar{\nu}_e\tau_R\phi_1^+ + \bar{e}_L\tau_R\phi_1^0) + (\bar{\nu}_\mu\tau_R\phi_2^+ + \bar{\mu}_L\tau_R\phi_2^0)\right] + H.c. \end{aligned} \tag{5}$$

It becomes clear that the h_1 term gives equal mass for the electron and the muon once $\langle\phi_S^0\rangle = v/\sqrt{2}$ develops. The h_2 term generates a mass for the τ lepton. If $h_3 = 0, \tau$ lepton number would be a good symmetry of the Lagrangian. The h_3 term induces a nonzero ν_τ mass in conjunction with the f term, which is allowed in the limit of exact $SU(2)_H$. The terms f and f' are crucial for the generation of the neutrino transition magnetic moment. We shall introduce explicit breaking of the $SU(2)_H$ symmetry, so that the relation $m_e = m_\mu$ which follows from Eq. (5) can be corrected.

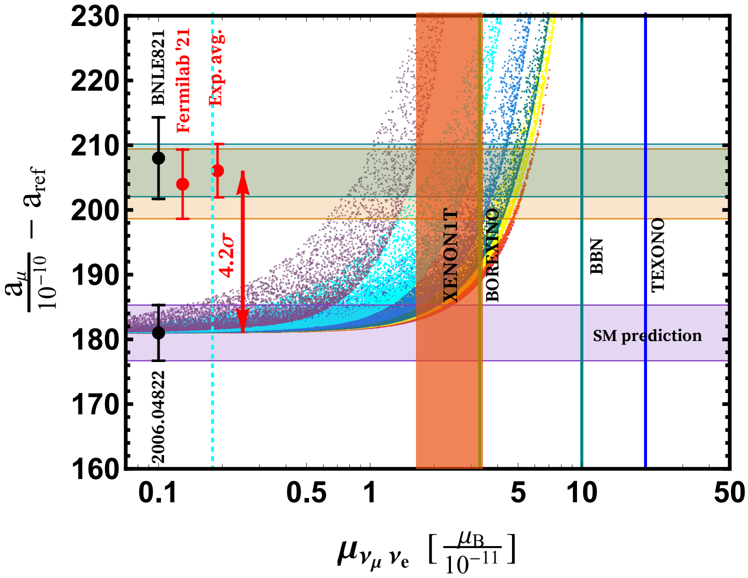

Figure 2: Theoretical predictions and experimental measurements of the muon anomalous magnetic moment and the neutrino transition magnetic moment.

The Lagrangian of the model does not respect lepton number. The $SU(2)_H$ limit of the model however respects $L_e - L_\mu$ symmetry. This allows a nonzero transition magnetic moment $\mu_{\nu_e\nu_\mu}$, while neutrino mass terms are forbidden – except for a loop-induced τ neutrino mass. Owing to the $SU(2)_H$ symmetry of the model, the two diagrams add in their contributions to the magnetic moment, while they subtract in their contributions to neutrino mass when the photon line is removed from these diagrams (for details, see Ref. [1]). The resulting neutrino magnetic moment is given by [1]

$$\mu_{\nu_\mu \nu_e} = \frac{f f'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2} \left\{ \ln \frac{m_{h^+}^2}{m_\tau^2} - 1 \right\} - \frac{1}{m_{H^+}^2} \left\{ \ln \frac{m_{H^+}^2}{m_\tau^2} - 1 \right\} \right] . \tag{6}$$

Predictions of neutrino magnetic moments (maximum achievable) for different neutrino mass models are summarized in Fig 1.

We have also shown that the models that induce neutrino magnetic moments, while maintaining their small masses naturally, also predict observable shifts in the muon anomalous magnetic moment [19, 29]. This shift is of the right magnitude to be consistent with the Brookhaven measurement as well as the recent Fermilab measurement of the muon $g-2$. This is pointing out the direct correlation between the magnetic moment of SM charged lepton and neutral lepton (neutrino) by showing that the measurement of muon $g-2$ by the Fermilab experiment can be an in-direct and novel test of the neutrino magnetic-moment hypothesis, which can be as sensitive as other ongoing-neutrino/dark matter experiments. Such a correlation between muon $g-2$ and the neutrino magnetic moment is generic in models employing leptonic family symmetry to explain a naturally large neutrino magnetic moment. In Fig. 2 we have shown a direct correlation between the muon anomalous magnetic moment and neutrino magnetic moment within our framework. For various other experimental tests of these models, see Refs. [1, 19, 23, 29–31].

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