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Majorana neutrino transition magnetic moment in a variant of Zee model with horizontal symmetry

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Abstract. A $SU(2)_H$ symmetric variant of Zee model of lepton flavor violation is presented and is shown to lead to neutrino transition magnetic moment of the order required to explain the solar neutrino deficit and the possible anticorrelation of solar neutrino flux with sunspot activity via VVO mechanism. The use of horizontal symmetry leads to totally degenerate neutrino states which may be combined to form a ZKM Dirac neutrino with naturally small mass.

Keywords. Majorana transition magnetic moment; horizontal symmetry; lepton flavour violation; VVO mechanism.

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1. Introduction

The latest chlorine data (Davis *et al* 1989) suggest a strong anticorrelation of solar neutrino flux with the solar magnetic activity which, however, is not supported by the latest Kamiokande data (Hirata *et al* 1989, 1990). If the apparent anticorrelation of solar neutrino flux with solar magnetic activity is confirmed to be a real effect, then it is natural to connect it with neutrino electromagnetic properties. A simultaneous explanation of the observed solar neutrino deficit as compared to the standard solar model prediction (Bahcall and Ulrich 1988; Bahcall 1989) and a possible time-variation of solar neutrino flux is possible if the electronic neutrino possesses a non-standard magnetic moment of the order of 10^{-10} to 10^{-11} μ_B where μ_B is the Bohr magneton (Cisneros 1971; Voloshin *et al* 1986). These are many orders of magnitude larger than the standard model prediction for the same (Lee and Schrock 1977). Such a large magnetic moment will cause the helicity of the neutrinos emitted in the core of the sun to flip in the kilogauss magnetic field present in the convective zone of the sun, converting a large fraction of them into a sterile species which does not interact with the detector. Two different types of magnetic moment are possible. A Dirac type magnetic moment would transform the neutrino into a sterile right handed neutrino. However, the observation of neutrino pulse from SN 1987A requires the Dirac magnetic moment to be smaller than 10^{-12} μ_B which is an order of magnitude smaller than that required for VVO mechanism (Voloshin *et al* 1986). Moreover, this scenario requires the introduction of extra right-handed neutrino species which may be aesthetically unappealing and also have serious repercussions for cosmology. However, a non-diagonal Majorana magnetic transition moment connecting a left handed neutrino of one generation to an active right-handed antineutrino of another generation via magnetic moment interactions of the type $\bar{\nu}_e \sigma_{\mu\nu} \nu^c_\mu F^{\mu\nu}$ is possible. Since ν^c_μ energy is below the weak interaction threshold, the observed solar neutrino deficit can be explained. This is also consistent with more stringent astrophysical bounds which follow from white dwarf cooling since the ν^c_μ's thus generated are automatically trapped and do not provide any additional channel of energy loss. Moreover, this scenario does not require introduction of extra neutrino species and no difficulties with SN 1987A arise. However, for this scenario to work, the two energy levels should be highly degenerate and require $m^2_{\nu_\mu} - m^2_{\nu_e} = \Delta m^2_\nu < 10^{-7}\mathrm{eV}^2$. However, in the presence of matter, because of the possibility of resonant enhancement (Lim and Marciano 1988; Akhmedov 1988) of flavor-changing spin precession (LMA mechanism) the VVO mechanism works for a wide range of neutrino masses given by the inequality: $10^{-8} < \Delta m^2_\nu < 10^{-4}\mathrm{eV}^2$.

In this work, a $\mathrm{SU}(2)_H$ symmetric variant of the Zee model (Zee 1980, 1985) of lepton flavor violation is presented where $\mathrm{SU}(2)_H$ acts between the first two leptonic generations. As observed by Voloshin (1988), the Dirac and the two Majorana mass terms form a $\mathrm{SU}(2)_H$ triplet whereas the Majorana magnetic transition moment is a singlet under this symmetry. Therefore, in the limit of an exact $\mathrm{SU}(2)_H$, neutrino magnetic moment being invariant under this symmetry is allowed whereas the mass being noninvariant under this symmetry is forbidden.

2. The Zee model and MNTM's

The model presented by Zee extends the scalar sector of the standard electroweak model by including an additional scalar doublet and a singly charged scalar field h apart from the standard Higgs doublet. This leads to new couplings of the type $M_{\alpha\beta}\varepsilon_{ij}\phi^i_\alpha\phi^j_\beta\, h$ where α and β distinguish between the different scalar doublets. The quantum numbers of h are such that it could couple to lepton doublets $\psi_{lL} = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L$ with $l = e, \mu, \tau$ via terms of the type

$$f_{ab}(\psi^i_{aL} C \psi^i_{bL})\varepsilon_{ij} h$$

where (a, b) denote the family indices, (i, j) the isospin indices and ε_{ij} is the anti-symmetric unit symbol. Also $f_{ab} = -f_{ba}$ because of Fermi statistics. The h field changes a charged lepton into an antineutrino. The couplings of the type $M_{\alpha\beta}\varepsilon_{ij}\Phi^i_\alpha\Phi^i_\beta h$ are now possible. Thus the new couplings relevant for spin precession are

$$f_{ab}(\psi^i_{aL} C \psi^i_{bL})\varepsilon_{ij} h + \mathrm{M}_{\alpha\beta}\varepsilon_{ij}\phi^i_\alpha\Phi^j_\beta h$$

where C is the Dirac charge conjugation matrix. Here neutrinos are Majorana particles and no right-handed neutrinos are introduced. There is no consistent way to assign a conserved lepton number to all these fields. For example, if $L(\Phi) = 0$ and $L(h^+) = -2$ so that the Yukawa interactions conserve L then the coupling $h\,\Phi^i_\alpha\Phi^j_\beta$ explicitly violates lepton number by two units.

At tree level, the neutrinos remain massless in this model. However, at one-loop level, radiatively induced neutrino masses can arise and are calculable. Moreover, off-diagonal transition moments of magnetic or electric type can be induced. Babu and Mathur (1987) studied Majorana neutrino transition moments [MNTM's] in this model and found that the model can provide a sufficiently large MNTM to the electronic neutrino provided there is a fourth generation of heavy leptons. However, it was subsequently shown by Liu (1989) that the Zee model cannot provide a sufficiently large MNTM while at the same time keeping the correspondingly induced mass correction at the phenomenologically acceptable level. The reason, of course, is that any internal heavy mass insertion contributing to MNTM's will also contribute to the induced mass so that the problem of naturalness is quite severe in the model. Apart from the problem of naturalness, Liu (1989) noted that in this model, the spin precession $\nu_{eL} \rightarrow \nu^c_{\mu,\tau R}$ is further suppressed by a prefactor arising from the mass difference of the two different Majorana neutrino states so that the spin precession is not efficient enough to realize the VVO or the LMA (Lim and Marciano 1988; Akhmedov 1988) scenario. MNTM's in the Zee model were also investigated by Pulido (1989) who also confirmed that the model cannot provide a sufficiently large MNTM for a naturally light neutrino unless additional symmetries are imposed on the model (Dhar and Dev 1992).

3. A $SU(2)_H$ symmetric variant of Zee model and MNTM's

It was Voloshin (1988) who first noted the different transformation properties of the magnetic moment and mass operators under a new symmetry $SU(2)_\nu$. The Dirac and the two Majorana mass terms for the neutrino form a $SU(2)_\nu$ triplet whereas the Majorana magnetic transition moment transforms as a singlet under this symmetry. Therefore, the imposition of $SU(2)_\nu$ symmetry will allow the invariant magnetic moment term but will forbid the noninvariant mass term for the neutrino. The $SU(2)_\nu$ invariant model can thus produce a sufficiently large MNTM for a naturally light neutrino. Voloshin himself, however, did not provide any example of how to implement this symmetry which does not commute with the standard electro-weak gauge group. Following Wolfenstein (1990) $SU(2)_\nu$ here it is identified with the horizontal symmetry $SU(2)_H$ where the $SU(2)_H$ acts between the first two leptonic generations. This lepton flavor symmetry is explicitly broken by the weak gauge interaction. In the case of Majorana neutrinos, $SU(2)_H$ is simply a horizontal symmetry between the first two leptonic generations broken explicitly only by the difference of the two Yukawa couplings viz.

$$\varepsilon = \frac{f_\mu - f_e}{2} = \frac{m_\mu - m_e}{2\langle H_0 \rangle} \approx 3 \times 10^{-4}$$

where f_e and f_μ are the Yukawa couplings of the two generations. The finite mass $m_\mu \neq m_e$ breaks $SU(2)_H$ down to $U(1)_N$ which ensures the conservation of $N_\mu - N_e$. In the exact $SU(2)_H$ limit, $\Delta m^2_{\nu_e\nu_\mu} = m^2_{\nu_\mu} - m^2_{\nu_e} = 0$ so that ν_e will pair up with ν^c_μ to form a ZKM (Zeldovich 1952; Konopinsky and Mahmoud 1953) type Dirac neutrino.

A $SU(2)_H$ symmetric variant of the Zee model can be constructed in the limit $m_e = m_\mu$ with the following assignments under $SU(2)_H$:

$$\psi_{L\, i\in SU(2)_{WS}}^{\, a\in SU(2)_H} = \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}; \quad T = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix},$$

$$\psi^a_R = (e \quad \mu)_R; \quad \tau_R.$$

The scalar sector now contains two additional $SU(2)_H$ doublets D and S apart from the standard Higgs which is a singlet under $SU(2)_H$:

$$D_i^a = \begin{pmatrix} d_e^0 & d_\mu^0 \\ D_e^- & D_\mu^- \end{pmatrix}; \quad S_i^a = (S_e^-, S_\mu^-), \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}.$$

After electroweak symmetry breaking, the two $SU(2)_H$ doublets of the Higgs sector mix to give the following physical scalars:

$$\begin{pmatrix} K_\pm \\ K'_\pm \end{pmatrix} = \begin{pmatrix} \cos\beta_\pm & \sin\beta_\pm \\ -\sin\beta_\pm & \cos\beta_\pm \end{pmatrix} \begin{pmatrix} D_i^a \\ S_i^a \end{pmatrix}$$

where the subscripts $\pm$ denote the $N_\mu - N_e = \pm 1$ values. The mixing angles of $N_\mu - N_e = \pm 1$ sectors are denoted by $\beta_\pm$ respectively and the mass eigenstates are $K_\pm$ and $K'_\pm$ where $M(K_\pm) \leqslant M(K'_\pm)$. Because of the approximate $SU(2)_H$ symmetry the mixing angles and mass eigenvalues in the $N_\mu - N_e = +1$ and $N_\mu - N_e = -1$ sectors differ only by $O(\varepsilon)$ corrections. The charged physical scalars $K_\pm$ and $K'_\pm$ are mixtures of doublet and singlet under weak isospin and they all contribute to the neutrino transition magnetic moment and the mass at one loop level. Where at tree-level, the neutrinos are not affected by the introduction of the new scalars $K_\pm$ and $K'_\pm$. The relevant diagrams for magnetic moment are given in figure 1, where the intermediate scalar particle could be any of the four charged physical scalars. Removal of the external photon line from these diagrams provides the transition mass to the neutrino. It is a straightforward matter to calculate the neutrino transition magnetic moment and transition mass from these diagrams. The contributions from the $N_\mu - N_e = +1$ and $N_\mu - N_e = -1$ sectors add for the magnetic moment and if the small differences between the parameters viz. masses, mixing angles and Yukawa couplings of the two sectors are neglected one obtains

$$\mu_{\nu_e\nu_\mu} = \frac{\mu_\beta}{8\pi^2} f_{e\tau} f_{\mu\tau} \sin(2\beta) m_e m_\tau \times \left[\frac{1}{M_K^2} \left\{ \ln\left(\frac{M_K^2}{m_\tau^2}\right) - 1 \right\} - \frac{1}{M_{K'}^2} \left\{ \ln\left(\frac{M_{K'}^2}{m_\tau^2}\right) - 1 \right\} \right]$$

for the magnetic transition moment where the approximation $m_\tau^2/M_{K,K'}^2 \ll 1$ has been made use of and the parameters of $N_\mu - N_e = +1$ and $N_\mu - N_e = -1$ sectors have been taken to be exactly equal. This can lead to a transition moment of requisite

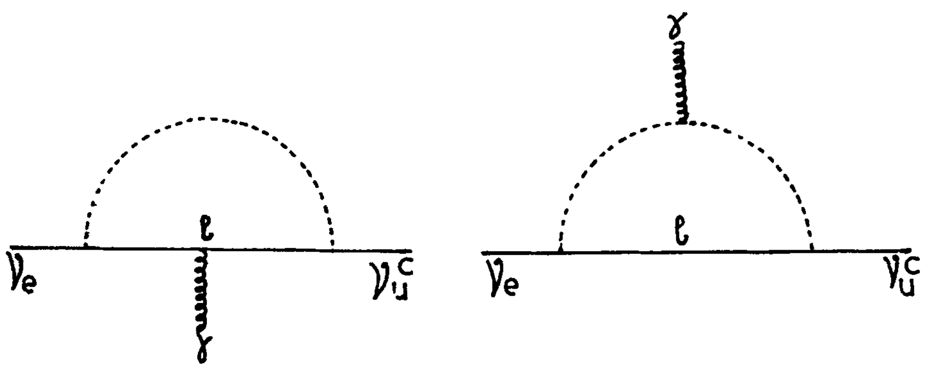

Figure 1.

magnitude for a wide range of values of Yukawa couplings with $f_{e\tau} f_{\mu\tau} \approx 10^{-2}$ to 10^{-3} and with masses of new scalars greater than the presently explored energy range (above 50 GeV).

The one-loop mass correction, on the other hand, is subject to cancellation from $N_\mu - N_e = +1$ and $N_\mu - N_e = -1$ sectors and one obtains

$$m_{\nu_e \nu_\mu} = \frac{m_\tau}{16\pi^2} (\sin(2\beta_+) f_+^{e\tau} f_+^{\mu\tau} \ln(M_{K^+}/M_{K'^+}) - \sin(2\beta_-) f_-^{e\tau} f_-^{\mu\tau} \ln(M_{K^-}/M_{K'^-}).$$

In the limit of exact $SU(2)_H$ symmetry, the masses, mixing angles and Yukawa couplings of $N_\mu - N_e = +1$ and $N_\mu - N_e = -1$ sectors are identical so that the one-loop contribution to mass vanishes. However, the parameters of the two sectors actually differ by $O(\varepsilon)$ corrections and the mass correction is suppressed to the phenomenologically acceptable electron volt range consistent with laboratory, astrophysical and cosmological constraints. The use of Voloshin symmetry in the model not only generates magnetic moment of desired order for VVO mechanism but also leads to degenerate neutrino states which may be combined to form a ZKM Dirac neutrino with naturally small mass.

Babu and Mohapatra (1989) have also proposed a $SU(2)_H$ symmetric model for large transition moment of the electronic neutrino. The $SU(2)_H$ in their model also acts between the first two leptonic generations and is gauged. The model utilizes two additional real triplets for spontaneous symmetry breaking. However, this leads to difficulties since the symmetry must be broken at very high energies, reintroducing fine tuning. In addition, $SU(2)_H$ has global anomalies, as there is an odd number of Weyl doublets.

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