MeV Tau Neutrino in Gauge Mediated Supersymmetry Breaking Model (Postprint)

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Abstract

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Full Text

Preamble

MeV Tau Neutrino in Gauge Mediated Supersymmetry Breaking Model

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Abstract

We describe a supersymmetric model that naturally accommodates an MeV tau neutrino within the framework of gauge mediated supersymmetry breaking. Lepton number violation is originally introduced in the messenger sector of the theory, generating a large slepton-Higgs mixing mass and a small lepton-higgsino mixing mass at one-loop. The scalar tau neutrino acquires a non-vanishing vacuum expectation value, resulting in a non-zero ν_τ mass in the range of (1–10) MeV.

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I. Introduction

A massive τ-neutrino with mass in the range of 1–10 MeV presents an interesting scenario for astrophysics and cosmology []. It should have a lifetime of 0.1–100 sec [] or a sufficient annihilation rate []. As summarized in Ref. [], such a neutrino can relax the big-bang nucleosynthesis bounds on the baryon density and the number of neutrino species; allow big-bang nucleosynthesis to accommodate a low ($< 20\%$) ^{4}He mass fraction or high ($> 10^{-4}$) deuterium abundance; significantly improve the agreement between the cold dark matter theory of structure formation and observations; and help explain how type-II supernova explosions occur.

Due to these useful phenomenological consequences, it is interesting to examine whether there exists a natural way to accommodate an MeV tau neutrino. This can be achieved by introducing right-handed neutrinos into the Standard Model (SM). To make the mass range natural, the Majorana mass scale of the right-handed neutrinos should be properly chosen, and fermion family symmetry may be further introduced to keep the e-neutrino and μ-neutrino light. This τ-neutrino must decay or annihilate—for example, into light neutrinos and a massless boson []—fast enough to avoid overclosure of the universe. Nevertheless, the above logic essentially places the explanation of neutrino masses in the same category as that of other fermion masses.

Within supersymmetry, which is the most favorable framework for physics beyond the SM, neutrino masses can have several alternative origins. This is simply because in this case, lepton number is no longer automatically conserved at tree level. By assuming only the conservation of baryon number, practically viable models can be constructed without contradiction to current experiments. These are the so-called R-parity violating models (with baryon number conservation). In such models, the possible new origins of neutrino masses can be typically classified into the following scenarios.

First is the non-vanishing sneutrino vacuum expectation values (vevs) []. If the sneutrino vevs are non-zero, neutrinos generally gain mass due to tree-level mixing with neutralinos, potentially generating neutrinos with masses of several MeV. The second scenario arises from lepton number violating interactions in the superpotential. There are two kinds of renormalizable interactions: bilinear and trilinear terms. In cases where the bilinear terms can be rotated away by redefining the Higgs superfield [], the lepton number violation can be entirely realized in the trilinear terms. These trilinear interactions induce neutrino masses at the loop level [].

However, the trilinear coupling constants are so constrained by phenomenological considerations [] that this mechanism cannot produce a τ-neutrino mass larger than 1 MeV within a reasonable range of supersymmetric mass scales. The third possibility lies in the soft supersymmetry breaking terms with lepton number violation []. The effect of lepton number violation is mediated to neutrino masses through loops. The simplest case is to introduce bilinear mass terms that mix the Higgs boson with scalar neutrinos. They induce mixing between neutrinos and higgsinos, which in turn generates neutrino masses via the see-saw mechanism. For soft masses around the weak scale, neutrino masses of several MeV can be generated [][1]. Both the first and third kinds of origin for MeV neutrinos rely on the deeper structure of the theory—namely the supersymmetry breaking mechanism—because they are closely related to the soft breaking sector.

Within the framework of minimal supergravity, Ref. [] studied R-parity violation characterized by bilinear terms in the superpotential. These are the most relevant terms for heavy neutrino masses. Generally, they result in sneutrino vevs that might be around 100 GeV. Such large values, however, do not necessarily mean 100 GeV heavy neutrino masses, because there is an almost alignment in the mass matrix []. In other words, by a suitable choice of basis, the bilinear terms are rotated away and the corresponding soft terms are almost rotated away. Effectively, there are only small sneutrino vevs in this basis which can give τ-neutrino masses ranging from sub-eV to [].

In this paper, we consider the MeV τ-neutrino as well as R-parity violation in the framework of gauge mediated supersymmetry breaking (GMSB). We note that it can be natural that even in the basis where the bilinear terms in the superpotential are absent, the theory still allows a relatively large sneutrino vev of about 1–10 GeV. For such a sneutrino vev, the lepton number breaking must not be spontaneous, otherwise the corresponding Goldstone boson would result in unacceptable consequences both in astrophysics [] and in Z decays []. Some explicit lepton number violations must be introduced further, such as soft supersymmetry breaking terms with lepton number violation. This scenario generates an MeV neutrino provided that the Zino mass is around 1000 GeV. It will be realized in GMSB in the next section.

II. The Model

In this section, we construct a simple model that accommodates an MeV τ-neutrino within the framework of GMSB. The lepton number violation is introduced originally in the messenger sector of the theory and is then communicated to the SM sector including the related soft supersymmetry breaking terms. The τ-neutrino mass appears naturally in a way that combines the first and third

[1] A recent discussion was made in Ref. [].

scenarios described above. We provide an explanation for the soft breaking mass terms with lepton number violation.

GMSB theory [] has drawn considerable attention recently. Supersymmetry breaking is communicated from the hidden sector to the observable sector of the theory via gauge interactions. The scale of supersymmetry breaking is comparatively low, so that flavor-changing neutral current processes are sufficiently suppressed. When considering an MeV τ-neutrino, we will make use of the observations of Dine and Nelson [], and Dvali et al. []. They noted that in GMSB the μ problem [] is rather severe: both the μ term (the mixing mass term of the two Higgs doublets) and its corresponding soft breaking $B\mu$ term can be generated at one-loop []. Either μ is at the weak scale and $B\mu$ is unnaturally large, or $B\mu$ is at the weak scale and μ is very small. While there are possible solutions to this problem [], we will not address it in this work. Instead, we apply a similar observation to the discussion of another mixing term—that between the lepton and Higgs doublets.

We extend the model of Dine and Fischler [] to include lepton number violation. To keep the other two neutrinos light, we assume a discrete family symmetry—a Z_3 symmetry among the $SU(2)$ doublets of the three generations. The gauge group of the model is just $SU(3) \times SU(2) \times U(1)$. The supersymmetric gauge interactions are uniquely determined and can be found in textbooks. Besides the fields of the particles in the minimal supersymmetric SM, such as the left-chiral lepton superfields and their $SU(3) \times SU(2) \times U(1)$ quantum numbers $L_i(1, 2, -1/2)$ for three families, the Higgs superfields $H_u(1, 2, +1/2)$ and $H_d(1, 2, -1/2)$ where $i = 1, 2, 3$ [], we introduce an additional set of chiral superfields, usually called the messenger sector:

$$S, S' = (1, 2, -1/2), \bar{S}, \bar{S}' = (1, 2, +1/2),$$
$$T, T' = (3, 1, 2/3), \bar{T}, \bar{T}' = (\bar{3}, 1, -2/3).$$

Furthermore, there are three gauge-singlet superfields, X, Y, and V. Y is responsible for supersymmetry breaking, X is related to electroweak symmetry breaking, and V to lepton number violation.

The superpotential of the model is written as follows, where W_1 conserves lepton number:

$$W_1 = m_1(\bar{S}'S + S'\bar{S}) + m_2(\bar{T}'T + T'\bar{T}) + m_3 S\bar{S} + m_4 T\bar{T} + m_5 V^2$$
$$+Y(\lambda_1 S\bar{S} + \lambda_2 T\bar{T} + \lambda_3 V^2 - 1) + \lambda_4 X(H_u H_d - \mu_2^2)$$

In the above equation, the Yukawa interactions are omitted as they are irrelevant to our discussion. W_2 violates lepton number but has Z_3 family symmetry:

$$W_2 = V(\lambda_5 H_u S + \lambda_6 L_i \bar{S})$$

The supersymmetry breaking is communicated to the observable sector by the messengers. The physics related to W_1 has been discussed thoroughly in Ref. []. The only difference is that we have introduced one more gauge-singlet V. For m_2 sufficiently large, V does not develop any vev. The form of the superpotential is not the most general one that follows from the symmetry principle. However, it is natural in the sense of 't Hooft due to the non-renormalization theorem in supersymmetry. μ_1 is the supersymmetry breaking scale. μ_2 fixes the electroweak scale, namely the vevs of the Higgs fields. It therefore contributes to higgsino masses as will be seen explicitly later.

For the superpotential W_2, as can be seen, it is the second term of Eq. (5) that violates lepton number. We have freedom to redefine $L_i \equiv L'_\tau$, which can be regarded as the weak eigenstate of the (ν_τ, τ) superfield. Then:

$$W_2 = V(\lambda_5 H_u S + \sqrt{3}\lambda_6 L'_\tau \bar{S})$$

This results in effective τ lepton number violating interactions by integrating out the heavy messengers:

$$W_{\text{eff}} = \sqrt{3}\mu_\tau L'_\tau H_u|_{\theta\theta} + \sqrt{3}B_{\mu_\tau} A'_\tau \phi_u + \text{h.c.},$$

where A'_τ and ϕ_u denote the scalar fields of the superfields L'_τ and H_u, respectively, and both μ_τ and B_{μ_τ} are generated through one-loop diagrams shown in Fig. 1 [Figure 1: see original paper]:

$$B_{\mu_\tau} \simeq \frac{\lambda_5\lambda_6}{16\pi^2}\mu_1 m_2$$

It is easy to see from Eq. (4) that μ_1^2 is the vev of the auxiliary component of Y. From Eq. (8), we have the relation:

$$B_{\mu_\tau} = \mu_\tau m_2$$

μ_1 is constrained by the soft masses of the superpartners of the SM particles. It is natural to take the messenger mass scale $\sim 10^3$ GeV and the supersymmetry breaking scale $\mu_1 \sim 10^4$ GeV. In this case, if B_{μ_τ} is chosen to be around the electroweak scale, μ_τ will be very small, which can be achieved by choosing the coupling product $\lambda_5\lambda_6$ appropriately. Phenomenologically it does not matter to have a small μ_τ. In fact, this is what we need, as we will see in the following. It should be noted that L'_τ and H_d appear in the superpotential in different ways, so that the term $L'_\tau H_u$ cannot be rotated away.

It is necessary to discuss the scalar potential of the theory to understand the sneutrino vevs. In this model, besides field Y, the fields that can have non-vanishing vevs are the sneutrinos in the slepton doublets A_i and the neutral components of the Higgs doublets ϕ_u and ϕ_d. Sneutrino vevs are determined by the minimum of the following neutral potential:

$$V_n = V_n^H + 2B_{\mu_\tau} v_i v_u + M_A^2 v_i^2 + \frac{1}{8}(g_1^2 + g_2^2)(v_u^2 + v_d^2 - v_i^2)^2$$

where V_n^H has not been written explicitly as it is the Higgs potential irrelevant to sneutrinos. The scalar lepton mass M_A^2 has been calculated in Ref. []. Neglecting the Yukawa contribution:

$$M_A^2 = \Lambda_S^2 - \frac{1}{2}M_Z^2 \cos 2\beta$$

with $\Lambda_S^2 = \frac{8}{16\pi^2}\lambda_6^2\mu_1^2$. g_1 and g_2 are the $U(1)$ and $SU(2)$ coupling constants. We expect $v_i \ll v_d$ or v_u so as to keep lepton universality. Therefore in Eq. (11), all terms of order v_i^3 and above have been dropped. Straightforward analysis shows that:

$$v_1 = v_2 = v_3 = B_{\mu_\tau} v_u/(M_A^2 + \frac{1}{2}M_Z^2 \cos 2\beta)$$

where $\tan\beta = v_u/v_d$. As we have seen, even after electroweak symmetry breaking, the Z_3 symmetry is still valid. In other words, only the τ'-sneutrino has a non-vanishing vev:

$$\sqrt{3}v_{\tau'} = B_{\mu_\tau} v_u/(M_A^2 + \frac{1}{2}M_Z^2 \cos 2\beta)$$

Numerically, $v_{\tau'}$ can be one order of magnitude lower than v_d, e.g., $v_{\tau'} \sim 10$ GeV by taking $M_A \sim 300$ GeV, $B_{\mu_\tau} \sim (50\text{ GeV})^2$. As mentioned before, non-vanishing $v_{\tau'}$ implies mixing between τ'-neutrino and neutralinos.

The term $L'_\tau H_u$ provides a mixing mass between $(\nu_{\tau'}, \tau')$ and higgsinos. The large B_{μ_τ} can also cause comparatively large fermion mixing. The B_{μ_τ} term, which is the mixing mass term between the slepton doublet A'_τ and Higgs doublet ϕ_u, induces a renormalization to the corresponding fermion mixing mass term between $(\nu_{\tau'}, \tau')$ and the higgsino $(\tilde{\phi}_u^+)$, which is the superpartner of ϕ_u. At one-loop level, this occurs through Zino (for neutral fermion mixing) or Wino (for charged fermion mixing), with A'_τ and ϕ_u being the virtual particles with B_{μ_τ} insertion, as shown in Fig. 2 [Figure 2: see original paper]. The loop effect is approximately:

$$m_{\tau H} \sim \frac{\sqrt{3}B_{\mu_\tau}}{16\pi^2} \times \frac{g_2^2}{M_2}$$

where M_2 is the Zino mass. Together with the contribution of μ_τ, the resulting fermion mixing mass is:

$$\sqrt{3}\mu_\tau + m_{\tau H} \simeq (50\text{ GeV})^2/(300\text{ GeV})$$

which implies $\mu_\tau \sim 0.1$ GeV. Requiring $B_{\mu_\tau} \sim (50\text{ GeV})^2$ gives $\mu_\tau \sim 0.03$ GeV due to Eq. (9). Plus the loop effect, $m_{\tau H} \sim \sqrt{3}B_{\mu_\tau}/(16\pi^2) \times (g_2^2/M_2)$.

Let us now consider the neutral fermion mixing, namely the mixing of ν'_τ and $\tilde{\phi}_u^0$. This will give the ν_τ mass. For this purpose, the full mass matrix of ν'_τ and neutralinos should be written down. The Lagrangian for the neutralino masses is given by:

$$\mathcal{L} = \frac{1}{2}(\nu'_\tau \tilde{\phi}_u^0 \tilde{\phi}_d^0 \tilde{Z} \tilde{X}) M (\nu'_\tau \tilde{\phi}_u^0 \tilde{\phi}_d^0 \tilde{Z} \tilde{X})^T + \text{h.c.},$$

where the mass matrix M is:

$$M = \begin{pmatrix} 0 & m_{\tau H} & 0 & av_{\tau'} & av_d \\ m_{\tau H} & 0 & -\mu_\tau & av_u & -\lambda_4 v_u \\ 0 & -\mu_\tau & 0 & -av_d & \lambda_4 v_d \\ av_{\tau'} & av_u & -av_d & M_{\tilde{Z}} & 0 \\ av_d & -\lambda_4 v_u & \lambda_4 v_d & 0 & M_{\tilde{X}} \end{pmatrix}$$

where $\tilde{\phi}_d^0$ and $\tilde{X}$ are the fermion components of H_d and X respectively, $a = (g_1^2 + g_2^2)^{1/2}$. The determinant of this matrix is approximately:

$\det(M) \simeq 2m_{\tau H} a^2 \lambda_4^2 v_{\tau'} v_u (v_d^2 + v_u^2)$

by taking $m_{\tau H} \ll$ electroweak scale. Therefore we have:

$m_{\nu_\tau} \simeq (m_{\tau H} v_{\tau'} v_u)/(v_d^2 + v_u^2)$

which can be naturally within the range (1–10) MeV. The eigenstate is:

$\nu_\tau = N_\nu(\nu'_\tau - (v_{\tau'}/v_d)\tilde{\phi}_d^0 + (v_{\tau'}/v_u)\tilde{\phi}_u^0)$

with N_ν being the normalization constant. If the induced mass $m_{\tau H}$ were vanishing, it is easy to see that the mass matrix in Eq. (15) would be of rank 4 (instead of 5), despite the sneutrino vev being non-vanishing. The absence of the conventional μ parameter is crucial for the τ-neutrino being very light compared to the weak scale. If a weak-scale μ parameter were included, the neutrino mass would be at the weak scale or so.

The mixing of the τ' lepton with charginos is not as interesting as that of neutralinos. It just renormalizes slightly the τ lepton and chargino masses. The related mass matrix is:

$$(\tau^c \tilde{\phi}_u^+ \tilde{W}^+) \begin{pmatrix} M_\tau & g_Y v_d & -g_Y v_{\tau'} \\ g_2 v_{\tau'} & \mu_\tau & g_2 v_d \\ 0 & M_{\tilde{W}} & 0 \end{pmatrix} (\tau \tilde{\phi}_d^- \tilde{W}^-)^T$$

where τ^c is the charge-conjugate field of the right-handed τ lepton, which has a Yukawa coupling g_Y with τ'^-. At this stage, muon and electron are still massless because of the Z_3 family symmetry. The physical τ lepton state is:

$\tau = N_\tau(\tau' + (v_{\tau'}/v_d)\tilde{\phi}_d^-)$

with N_τ being the normalization constant.

In this kind of supersymmetric model, τ-neutrino only decays via W-boson exchange, $\nu_\tau \to e^+e^-\nu_e$. Cosmology and astrophysics require a ν_τ lifetime smaller than 100 sec []. That means a heavier ν_τ is favored. Taking $m_{\nu_\tau} = 10$ MeV, the lifetime is []:

$\tau_{\nu_\tau} \simeq \frac{192\pi^3}{G_F^2 m_{\nu_\tau}^5 |V_{e\tau}|^2} \approx 0.1\ \text{sec}/|V_{e\tau}|^2$

In this case, the e-τ CKM-like mixing is required to be $|V_{e\tau}| \geq 0.05$[2]. This needs to be studied after including masses for e, μ and their neutrinos.

Phenomenologically, this model predicts lepton universality violation in τ lepton decays. This is because ν_τ and τ in Eqs. (17) and (19) do not coincide in form.

[2]This requirement is not totally unreasonable. Although the mass hierarchy of neutrinos is huge, that of charged leptons is not. In certain extreme situations, the relation $|V_{e\tau}| \sim 0.3$ might hold.

Compared to the e-ν_e or μ-ν_μ weak transition, the τ-ν_τ transition amplitude is suppressed by a factor $N_\nu N_\tau(1+v^2_{\tau'}/v^2_d)$. This factor can be effectively absorbed into the gauge interaction coupling constant g_τ. Therefore it simply measures τ lepton universality violation. With a reasonable choice of $\tan\beta$, like $\tan\beta = 2.2$, for $v_{\tau'} \sim 10$ GeV, the e-τ universality violation is at the 10^{-3} level:

$g_e : g_\tau = 1 : 0.996$

which is still consistent with experiment [], but near the experimental limit.

III. Summary and Discussions

In summary, we have described a supersymmetric model that can naturally accommodate an MeV tau neutrino within the framework of GMSB. The lepton number violation is introduced in the messenger sector of the theory, which is then communicated to the SM sector at one-loop level. It turns out that a large B_{μ_τ} term and a small μ_τ term (see Eqs. (7, 8)) are generated. Furthermore, a non-vanishing sneutrino vev (see Eq. (13)) is produced. These results cause, in an interesting manner, a non-zero ν_τ mass that is right in the range of (1–10) MeV. Such a mass for the tau neutrino and the phenomenological consequence of lepton universality violation can be verified by experiments in the near future.

We have noted that this kind of model is specific as far as the μ-term is concerned. That term is not necessary in the model. The electroweak symmetry is broken due to the introduction of the μ_2 term, which can be regarded as an expedient. The explanation of μ_2, and hence radiative electroweak symmetry breaking, is beyond the scope of this paper. It is reasonable to discuss it when the μ problem in GMSB gets a satisfactory understanding.

This model is of theoretical interest. Firstly, the mechanism of supersymmetry breaking is still an open problem. MeV neutrinos in GMSB are worthy of exploration. Secondly, although the MeV neutrino is not intrinsic to GMSB, the way to achieve it in this paper is very different from that in supergravity []. It naturally allows a rather large sneutrino vev while the bilinear R-parity violation is small. This scenario may have other physical consequences, e.g., in the flavor problem []. A detailed investigation of these is left for future work.

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Figure Captions

Fig. 1 Superfield diagrams for generating μ_τ (a) and B_{μ_τ} (b). The internal lines with (without) a "×" denote a messenger field propagator. The Y field can also be attached to the V line.

Fig. 2 One-loop diagram for neutral fermion mixing due to the B_{μ_τ} term which is denoted as "×". $\tilde{Z}$ stands for Zino.

Figures (a) (b)
Fig. 1
Fig. 2

Note: Figure translations are in progress. See original paper for figures.