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Abstract

An understanding of the lepton masses within the framework of SUSY is presented.A family symmetry is introduced. Sneutrino VEV breaks this symmetry. The tau mass is due to the Higgs VEV, and muon mass purely from the sneutrino VEV. A viable model is constructed, which predicts $(1-10)$ MeV #23;#28; .

Full Text

Preamble

Supersymmetry for Flavors

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Abstract

An understanding of the lepton masses within the framework of SUSY is presented. A family symmetry is introduced, which is broken by sneutrino VEVs. The tau mass arises from the Higgs VEV, while the muon mass originates purely from the sneutrino VEV. A viable model is constructed that predicts a ν_τ mass in the range (1-10) MeV.

1. Introduction

The naturalness of the Standard Model (SM) may require the existence of low-energy supersymmetry (SUSY). The flavor puzzle of the SM—namely the fermion masses, mixings, and CP violation—demands new physics for its understanding. It would be desirable if SUSY could also provide (at least partial) insight into the flavor problem.

Let us examine the fermion mass pattern. The observed hierarchy is that the third generation is much heavier than the second, which in turn is much heavier than the first. Does this imply a family symmetry? We assume the answer is yes. Consider the charged leptons: by imposing a Z_3 cyclic symmetry among the $SU(2)$ doublets L_i ($i = 1, 2, 3$) of the three generations, the Yukawa interactions yield a democratic mass matrix. This matrix has rank 1, so only the tau lepton acquires mass; the muon and electron remain massless.

The crucial question is how the family symmetry breaks. Naively, this could be achieved by introducing additional Higgs fields. We address this problem within SUSY. We observe that SUSY naturally provides Higgs-like fields—the scalar neutrinos. Furthermore, if the vacuum expectation values (VEVs) of the sneutrinos $\tilde{\nu}_i$ are non-vanishing, they contribute to fermion masses in addition to the Yukawa interactions. This motivates our proposal that the family symmetry is broken by sneutrino VEVs.

A remark is in order: the sneutrino VEV alone is insufficient for electroweak symmetry breaking (EWSB); Higgs fields remain necessary. As we will see, v_i is typically (5-10) GeV. Such a VEV is, however, too large to accommodate neutrino oscillation data. Our point is that this sneutrino VEV breaks a family symmetry, which can be useful for understanding the charged lepton masses.

Focusing on the lepton sector, the Z_3 family symmetry implies that Yukawa interactions only give the tau lepton mass: $m_\tau \simeq y v_d$, where y is the coupling constant and $v_d \sim 100$ GeV is the Higgs VEV. Taking $y \sim 10^{-2}$ yields a realistic m_τ. The muon mass is zero at this level. To make the model phenomenologically viable, we find that symmetry-breaking parameters of order 10^{-2} are needed. The muon mass then arises from the family symmetry breaking via $v_i \neq 0$.

2. Challenging Problems

Immediately, the following questions challenge the scenario described above:

1. Do rare decays like $\mu \to e\gamma$ contradict experimental data?
2. Is m_{ν_τ} too large? Roughly, it is expected to be $g_2^2/M_Z \sim 100$ MeV.
3. How can we reconcile the parameter values with experimental constraints?

To overcome these difficulties, we make the following assumptions respectively.

First, we introduce a large (weak-scale) mixing mass term between the Higgs scalar and slepton $\tilde{L}_3$: $B_{\mu 3}\tilde{H}_u\tilde{L}_3$. This term breaks SUSY softly. Because it explicitly violates lepton number, no massless Majoron (the Goldstone boson corresponding to spontaneous lepton number violation) appears. Note that the trilinear R-parity violating interactions alone are insufficient to keep the would-be Majoron from being light.

Second, in the superpotential, the bilinear mixing mass terms like $\mu_3 H_u L_3$ and $\mu H_u H_d$ should be small. We take $\mu_3 = 0$ and $\mu = 0$. In this way, $m_{\nu_\tau} = 0$ at tree level, which may avoid the difficulty of Question 2. Note that EWSB is achieved by an alternative superpotential.

Third, we adopt the Z_3 family symmetry in the ordinary Yukawa and trilinear R-parity violating interactions. Because of this, processes like $\mu \to 3e$ and $\mu \to e\gamma$ do not occur. This symmetry can be regarded as accidental at low energy.

The relevant superpotential is

$$W = y_j(L_i)H_d E^c + \lambda' X(H_u H_d - \mu^2) + \lambda_j(L_1 L_2 + L_2 L_3 + L_3 L_1)E^c,$$

where the last term is for EWSB, λ' is a coupling constant, X is a singlet superfield, and μ is at the weak scale. Baryon number conservation is assumed. Eq. (1) reproduces the lepton masses as planned.

It is easier to work in the mass eigenstates of the Yukawa interactions:

$$W = y_\tau L_\tau H_d E^c_\tau + L_e L_\mu(\lambda_\mu E^c_\mu + \lambda_\tau E^c_\tau) + \lambda' X(H_u H_d - \mu^2),$$

where the left-handed leptons are mixtures of the original fields, and (ν_i, e_i) are the fermionic components of L_i. The primed fields denote the physical leptons after mixing with neutralinos and charginos.

From Eq. (2), we see that rare decays like $\tau \to 2e\mu$ and $\tau \to 3\mu$ have branching ratios $\sim 10^{-7}$ if $m_{\tilde{\nu}_i} \simeq 100$ GeV. The decay $\mu \to 3e$ does not occur.

At the quantum level, a comparatively large neutrino mass is inevitably induced due to the large lepton-number violation in the $B_{\mu 3}$ term. It occurs at one-loop with Zino exchange. Therefore $m_{\nu_\tau} \neq 0$ at one-loop, which will be studied further. Is it natural in a theory where $B_{\mu 3}$ is large, μ_3 is vanishingly small, and m_{ν_τ} is consistent with experiment?

3. A Model of GMSB

Within the framework of gauge-mediated SUSY breaking (GMSB), the scenario posed in the last question can be realized naturally. Lepton number violation is introduced originally in the messenger sector and is then communicated to the SM sector, including the related soft SUSY breaking terms. We make use of observations regarding the μ-problem in GMSB.

It was noted that both the μ term and its corresponding soft-breaking B_μ term can be generated at one-loop. Either μ is at the weak scale and B_μ is unnaturally large, or B_μ is at the weak scale and μ is very small. This is not a problem in our model because the EWSB mechanism in Eq. (1) does not need the μ term. However, we apply a similar observation to the mixing of H_u and L_3.

The messengers are introduced with the following $SU(3)\times SU(2)\times U(1)$ quantum numbers:

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

Two additional gauge singlets are introduced: Y for SUSY breaking and V for lepton number violation. The superpotential is then

$$W_{\text{total}} = W_1 + W_2,$$

with

$$W_1 = m_1(\bar{S}'S+S'\bar{S})+m_2(\bar{T}'T+T'\bar{T})+m_3S\bar{S}+m_4T\bar{T}+m_5V^2+Y(\lambda_1S\bar{S}+\lambda_2T\bar{T}+\lambda_3V^2),$$

and

$$W_2 = V(\lambda_5 H_u S + \lambda_6 L_3 \bar{S}),$$

where μ_1 is the SUSY breaking scale. The lepton number violation resides in W_2.

By integrating out the heavy messengers, the effective Lagrangian related to lepton number violation is

$$\mathcal{L}_{\text{eff}} = \mu_3 L_3 H_u|_{\theta\theta} + B_{\mu 3}\tilde{L}_3\tilde{H}_u + \text{h.c.},$$

with $\mu_3 = \mu^2$ and $B_{\mu 3} = \mu_3\mu_1/m_3$. This is precisely what we need, with $B_{\mu 3}$ taken to be at the weak scale. Typically $1/m_3 \sim 100$ TeV, so μ_3 is very small if $B_{\mu 3}$ is at the weak scale.

From the scalar potential, the sneutrino VEV is obtained as

$$v_3 = \frac{B_{\mu 3} v_u}{2M_A^2 + M_Z^2 \cos 2\beta} \approx (60\text{ GeV})^2.$$

Numerically, $v_3 \sim 300$ GeV. A nonzero v_3 implies mixing between neutrino ν_3 and the neutralinos. In addition, $B_{\mu 3}$ causes comparatively large ν_3-Higgsino mixing at one-loop, with $m_{3H} \simeq M_{\tilde{Z}} \sim 0.1$ GeV.

The τ neutrino mass should be obtained from the full neutralino mass matrix. It gives

$$m_{\nu_\tau} \simeq \frac{m_{3H} v_3}{\sqrt{a}} \sim (1\text{-}10)\text{ MeV},$$

with $a = (1 + g_2^0)$. This heavy ν_τ can decay to $e^+e^-\nu_e$. We later noted that ν_τ can also decay to gravitino + photon with a longer lifetime. In writing down the expressions for the physical ν_τ and τ states in Refs. [**?**] and [**?**], the gaugino masses were neglected. In fact, ν_3 mixes with the photino.

4. Discussion

The idea about fermion masses presented in this model essentially depends on SUSY. A (1-10) MeV ν_τ is a consequence of this VEV. A model with large sneutrino VEV exists. It should be noted that L_3 and H_d appear in the superpotential in different ways, so the VEV cannot be rotated away by redefining the Higgs superfield.

The atmospheric neutrino anomaly must be explained by introducing a sterile neutrino, which is also necessary from Big Bang Nucleosynthesis constraints. The extension of this idea to the quark sector can be found in Ref. [**?**].

The $B_{\mu 3}$ term breaks the family symmetry explicitly. It would be more appealing if the family symmetry breaking were spontaneous in some clever model.

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References

1. G. ' t Hooft, in *Recent Developments in Gauge Theories*, ed. G. ' t Hooft (Plenum, New York, 1980).
2. [Reference missing in original]
3. D. Du and C. Liu, Mod. Phys. Lett. A **8** (1993) 2271; A **10** (1995) 1837; C. Liu, Mod. Phys. Lett. A **12** (1997) 329.
4. C. Aulakh and R. Mohapatra, Phys. Lett. B **119** (1982) 136; L. Ibáñez and G. Ross, Nucl. Phys. B **368** (1991) 3.
5. For a review, see M. Dine, in *Fields, Strings and Duality*, TASI96, eds. C. Efthimiou and B. Greene (World Scientific, 1997), p. 813.
6. [Reference missing in original]
7. M. Dine and A.E. Nelson, Phys. Rev. D**48** (1993) 1277; G. Dvali, G.F. Giudice and A. Pomarol, Nucl. Phys. B **478** (1996) 31.
8. [Reference missing in original]

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