Soft supersymmetry breaking terms from A_4 lepton flavor symmetry

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We study the supersymmetric model with the A_4 lepton flavor symmetry, in particular soft supersymmetry breaking terms, which are predicted from the A_4 lepton flavor symmetry. We evaluate soft slepton masses and A-terms within the framework of supergravity theory. Constraints due to experiments of flavor changing neutral current processes are examined.

1 Introduction

Recent experiments of the neutrino oscillation go into the new phase of precise determination of mixing angles and mass squared differences. Those indicate the tri-bimaximal mixing for three flavors in the lepton sector [1]. One of natural models realizing the tri-bimaximal mixing has been proposed based on the non-Abelian finite group A_4 [2].

On the other hand, the supersymmetric extension of the standard model is one of interesting candidates for physics beyond the weak scale. Flavor symmetries realizing realistic quark/lepton mass matrices would lead to specific patterns of squark and slepton mass matrices as their predictions, which could be tested in future experiments. The purpose of this paper is to study which pattern of slepton mass matrices is predicted from the A_4 model and to examine whether the predicted pattern of slepton mass matrices is consistent with the current FCNC experimental bounds, based on [3].

Now, we consider the supersymmetric A_4 model based on [4]. Under the A_4 symmetry, the chiral superfields for three families of the left-handed lepton doublets L_I $(I = e, \mu, \tau)$ are assumed to transform as triplets, while the right-handed ones of the charge lepton singlets R_e, R_μ and R_τ are A_4 singlet, and non-trival singlets. The Z_3 and $U(1)_F$ charges are also assigned. The flavor symmetry is spontaneously broken by vacuum expectation values (VEV) of two triplets, χ_i, χ'_i, and by one singlet, χ, which are $SU(2)_L \times U(1)_Y$ singlets.

The superpotential is given by the effective one with the cut-off scale Λ. In order to obtain the natural hierarchy among lepton masses m_e, m_μ and m_τ, the Froggatt-Nielsen mechanism [5] is introduced as an additional $U(1)_F$ flavor symmetry under which only the right-handed lepton sector is charged.

The VEVs of gauge singlet scalar fields χ, χ_i and χ'_i are given by minima in the scalar potential. Actually, they are estimated as $\mathcal{O}(\tilde{\alpha})$ in the Ref.[3, 4], where $\tilde{\alpha}$ is the magnitude of the VEVs divided by Λ. The magnitude is estimated by the neutrino experimental data. That is, the scale $\Lambda \simeq 10^{14}$GeV gives $\tilde{\alpha} \sim \mathcal{O}(10^{-2})$ in the case with $\tan\beta = 3$ and yukawa couplings, $|y_\tau| \simeq |y_1| \simeq |y_2| \simeq 1$.

The charged lepton mass matrix becomes diagonal and the neutrino mass matrix can be simplified at the leading order as shown in ref.[4]. Then, the tri-bimaximal mixing is found for the lepton flavor mixing matrix. The next leading terms, $\mathcal{O}(\tilde{\alpha})$, modify the results. The lepton mixing angles are changed by $\mathcal{O}(\tilde{\alpha})$. For example, the deviations from the diagonal charged lepton mass matrix are estimated as $\theta_{R12} \sim \frac{m_e}{m_\mu}\mathcal{O}(\tilde{\alpha})$ and $\theta_{L12} \sim \mathcal{O}(\tilde{\alpha})$.

2 Soft SUSY breaking terms

We study soft SUSY breaking terms, i.e. soft slepton masses and A-terms, which are predicted from the A_4 model discussed in the introduction.

First, we study soft scalar masses. Within the framework of supergravity theory, soft scalar mass squared is obtained as [6]

$$m^2_{\bar{I}J} K_{\bar{I}J} = m^2_{3/2} K_{\bar{I}J} + |F^{\Phi_k}|^2 \partial_{\Phi_k} \partial_{\bar{\Phi}_k} K_{\bar{I}J} - |F^{\Phi_k}|^2 \partial_{\bar{\Phi}_k} K_{\bar{I}L} \partial_{\Phi_k} K_{\bar{M}J} K^{L\bar{M}}. \tag{1}$$

The flavor symmetry $A_4 \times Z_3$ requires the following form of Kähler potential for left-handed and right-handed leptons

$$\begin{aligned} K^{(0)}_{\text{matter}} &= a(Z, Z^\dagger)(L^\dagger_e L_e + L^\dagger_\mu L_\mu + L^\dagger_\tau L_\tau) \\ &\quad + b_e(Z, Z^\dagger) R^\dagger_e R_e + b_\mu(Z, Z^\dagger) R^\dagger_\mu R_\mu + b_\tau(Z, Z^\dagger) R^\dagger_\tau R_\tau \ , \end{aligned} \tag{2}$$

at the leading order, where $a(Z, Z^\dagger)$ and $b_I(Z, Z^\dagger)$ for $I = e, \mu, \tau$ are generic functions of moduli fields Z. This $K^{(0)}$ is the prediction of the A_4 model that three families of left-handed slepton masses are degenerate.

However, the flavor symmetry $A_4 \times Z_3$ is broken to derive the realistic lepton mass matrices and such breaking introduces corrections in the Kähler potential and the form of slepton masses. The correction terms of diagonal elements in the matter Kähler potential are estimated as $\mathcal{O}(\tilde{\alpha})$. Off-diagonal Kähler metric entries for both left-handed and right-handed leptons appear at $\mathcal{O}(\tilde{\alpha}^2)$. The leptonic FCNC is induced by off diagonal elements of scalar mass squared matrices in the diagonal basis of the charged lepton mass matrix. For example, $(\tilde{m}^2_L)_{12}$, which has a strong constraint on from FCNC experiments [7], is estimated as $(\tilde{m}^2_L)_{12}/m^2_{\text{SUSY}} = \mathcal{O}(\tilde{\alpha}^2)$, where m_{SUSY} denotes the average mass of slepton masses and it would be of $\mathcal{O}(m_{3/2})$. Because of $\tilde{\alpha} \sim 0.03$ for $y_\tau \simeq 1$, our prediction, $(\tilde{m}^2_L)_{12}/m^2_{\text{SUSY}} = \mathcal{O}(\tilde{\alpha}^2) = \mathcal{O}(10^{-3})$, would be consistent with the current experimental bound. Similarly, we can estimate $(\tilde{m}^2_R)_{12}/m^2_{\text{SUSY}}$ and results are the same. The D-term and radiative corrections are also discussed in Ref.[3].

Now, we examine the mass matrix between the left-handed and the right-handed sleptons, which is generated by the so-called A-terms. The A-terms are trilinear couplings of two sleptons and one Higgs field. After the electroweak symmetry breaking, these A-terms provide us with the left-right mixing mass squared $(m^2_{LR})_{IJ} = h_{IJ} v_d$.

When we consider the leading order of Kähler potential $K^{(0)}_{\text{matter}}$, the (2,1) entry of $(\tilde{m}^2_{LR})_{IJ}$, which has a strong constraint, vanishes at the leading order. However, such a behavior is violated at the next order, because the diagonal (1,1) and (2,2) entries of Kähler metric have non-degenerate corrections of $\mathcal{O}(\tilde{\alpha})$. Then, the h_{IJ} contribution to the (2,1) entry of $(\tilde{m}^2_{LR})_{IJ}$ is estimated as $(\tilde{m}^2_{LR})_{21} \sim \mathcal{O}(\tilde{\alpha}^2 m_\mu m_{3/2})$. Furthermore, the off-diagonal elements of Kähler metric have $\mathcal{O}(\tilde{\alpha}^2)$ of corrections, and these corrections also induce the same order of $(\tilde{m}^2_{LR})_{21}$, i.e. $(\tilde{m}^2_{LR})_{21} = \mathcal{O}(\tilde{\alpha}^2 m_\mu m_{3/2})$. Similarly, we can estimate the (1,2) entry and obtain the same result, i.e., $(\tilde{m}^2_{LR})_{12} = \mathcal{O}(\tilde{\alpha}^2 m_\mu m_{3/2})$ when $\tilde{\alpha} > m_e/m_\mu$. These entries have the strong constraint from FCNC experiments as $(\tilde{m}^2_{LR})_{12}/m^2_{\rm SUSY} \leq \mathcal{O}(10^{-6})$ and the same for the (2,1) entry for $m_{\rm SUSY} = 100$ GeV. However, the above prediction of the A_4 model leads to $(\tilde{m}^2_{LR})_{12}/m^2_{\rm SUSY} = \mathcal{O}(10^{-7})$ for $m_{\rm SUSY} = 100$ GeV and $\alpha \sim 0.03$, and that is consistent with the experimental bound.

Now, we discuss the contributions of F_Φ/Φ and F_{χ_i}/χ_i, where Φ is a Froggatt-Nielsen field. There is a possibility that F_Φ/Φ leads large off-diagonal elements because each right-handed charged lepton has a different $U(1)_F$ charge. The contribution to the (1,2) entry is estimated as $\mathcal{O}(\tilde{\alpha}^2 m_\mu m_{3/2})$. This result is the same as the above.

On the other hand, $F_{\chi_i}/\chi_i (\equiv A_i)$ contributes to $(\tilde{m}^2_{LR})_{21}$ as $m_\mu \tilde{\alpha}(A_2 - A_1)$. That is, we estimate $(\tilde{m}^2_{LR})_{21}/m^2_{\rm SUSY} \sim 10^{-5} \times (A_2 - A_1)/m_{3/2}$ for $\tilde{\alpha} \sim \mathcal{O}(10^{-2})$. Thus, if $A_2 \neq A_1$ and $A_i = \mathcal{O}(m_{3/2})$, this value of $(\tilde{m}^2_{LR})_{21}/m^2_{\rm SUSY}$ would not be consistent with the experimental bound for $m_{\rm SUSY} = 100$ GeV. Hence, a smaller value of $\tilde{\alpha}$ like $\tilde{\alpha} = \mathcal{O}(0.001)$ would be favorable to be consistent with the experimental bound and that implies a large $\mathcal{O}(1)$ coupling. Alternatively, for $\tilde{\alpha} \sim \mathcal{O}(10^{-2})$ it is required that $A_1 = A_2$ up to $\mathcal{O}(0.1)$. If the non-trivial superpotential leading to SUSY breaking does not include χ_i, i.e. $\langle \partial_{\chi_i} W \rangle = 0$, we can realize that situation. Hence, we obtain the degeneracy between A_i, i.e., $A_1 = A_2 = A_3$ up to $\mathcal{O}(\tilde{\alpha} m_{3/2})$. In this case, $(\tilde{m}^2_{LR})_{21}$ is suppressed and we can estimate $(\tilde{m}^2_{LR})_{21}/m^2_{\rm SUSY} \sim \tilde{\alpha}^2 m_\mu/m_{3/2} = \mathcal{O}(10^{-6})$ for $\tilde{\alpha} \sim \mathcal{O}(10^{-2})$. This value is consistent with the experimental bound.

Similarly to slepton masses, radiative corrections to A-terms do not change drastically the above results. Note that Yukawa couplings are small, in particular the first and second families.

3 Conclusion

We have studied soft SUSY breaking terms, which are derived from the A_4 model. Three families of left-handed slepton masses are degenerate, while three families of right-handed slepton masses are, in general, different from each other. In the wide parameter region, the FCNCs predicted in the SUSY A_4 model are consistent with the current experimental bounds. Thus, the non-Abelain flavor symmetry in the A_4 model is useful not only to derive realistic lepton mass matrices, but also to suppress FCNC processes.

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