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Type-II seesaw in SO(10) theories with spontaneous CP violation

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Abstract We propose a possibility of spontaneous CP-violation (SCPV) at high scale in a SUSY SO(10) theory. The model is L-R symmetric SUSY SO(10) with 10 and 126 dimensional Higgs generating fermion masses, and the CP phase is generated through complex VEV of B-L breaking 126 Higgs. The model can have potential applications in explaining fermion masses, ν masses *via* type- II seesaw mechanism and Leptogenesis as well.

Keywords Susy So(10), spontaneous CP violation, GUT's

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1. Introduction

Understanding fermion masses and mixings is one of the longstanding challenges of theoretical particle physics. The various neutrino oscillation experiments have now established that neutrinos have masses, and that they mix among themselves. Grand Unified Theories (GUTs) provide a powerful tool for understanding fermion masses, and relations among them.

CP violation (CPV) was discovered experimentally about four decades ago, but its origin still remains one of the fundamental open questions in particle physics. CPV is directly observed only in the decays of the Kaons and B-mesons. At least four aspects of CPV are observed in nature - CPV in quark sector [1,2], in lepton sector, generation of BAU (baryon asymmetry of the Universe), and strong and SUSY CP problems. In this paper, we shall address its manifestation in the first two cases only.

Within the premises of the standard model (SM) model, neutrinos are massless, so there is no mixing and no CPV in the neutrino sector. However, the existence of ν masses is a well established fact now, and hence any theory which can explain them would also imply CPV in leptonic (CPV-L) sector in principle. The latter might be detected in future experiments to be performed at neutrino factories. Indirect evidence for the CPV-L may also be provided by forthcoming experiments on ν-less $\beta\beta$ decay (majorana phases). Existence of matter dominated Universe is another evidence of CPV, but it has been established that within the SM, it is not possible to generate observed BAU, partly due to smallness of CPV in SM (CKM phase). This provides motivation for considering new sources of CPV beyond the SM-CKM mechanism (*e.g.* through CPV from SUSY breaking sector). In gauge theories, there are two possibilities of CPV - explicit (hard) CP breaking at the Lagrangian level through complex Yukawa couplings (as in SM), or spontaneous (soft) CP breaking by the vacuum *via* complex VEV (SCPV).

SCPV at higher scales seems to be an interesting proposition to explain the origin of CPV in nature since all the couplings of the Lagrangian are real due to CP invariance at the Lagrangian level. CP is broken only through phases in VEV [3,4]. There has been quite significant amount of works in literature addressing the question of SCPV, an incomplete list is given as [5-11]. It has been a known difficulty with SUSY theories that they cannot generate CP breaking spontaneously. This is because they lead to a real CKM matrix. A recent analysis [12] of the present experimental data provides clear evidence for a complex CKM matrix. These experimental findings [13] of the γ angle inspires to ask the question if we can have a SUSY extension of the SM with SCPV and a complex CKM matrix. In fact some work has already been done in this line [6-10]. There they introduce extra vector-like quark which mixes with standard quarks and lead to a non-trivial phase in 3x3 CKM matrix [7], VEV of 126 Higgs in SUSY SO(10) theory is complex [6], or add extra Higgs [8], extension of SM with a $SU(2)_L$ singlet quark and a singlet Higgs field [11], has been considered. Issues of yukawa sector fits as well as problem of CKM CP violation in the minimal setup has been discussed in detail in [14] also.

2. Motivation for the present work

In the present work, we have attempted to find a possible model to generate a CP phase spontaneously in L-R symmetric SUSY SO(10) theory, in particular in context of generating neutrino masses and mixings *via* type-II seesaw mechanism. In the framework of SO(10) GUT SCPV was first discussed in [15]. In the present model, B-L symmetry is broken by a 126 dim Higgs, which also contributes to fermion masses along with a 10 dim Higgs [16,17]. This theory seems to be too attractive to generate small masses – it has a right handed majorana neutrino (RHMN) to implement see-saw mechanism, naturally contains B-L symmetry needed to keep the RHMN below the Planck scale, provides a group theoretical explanation of why neutrinos are majorana particles, has automatic R-parity conservation which leads to natural conservation of baryon and lepton number symmetry prior to symmetry breaking, provides a simple mechanism for explaining origin of matter in the Universe *etc.* It has been shown that type-I see-saw predictions of this model are in contradiction with experiments [16,18]. Then, type-II see-saw [19] for neutrino masses [20] was suggested to explain the data. In [21] $b-\tau$ unification was used to explain the masses and mixings. In [22], CPV was introduced thorough complex Yukawa couplings (of course this list is incomplete!), and it was found that compatibility with data requires

CKM phase to be outside the first quadrant (whereas the SM CKM phase is in first quadrant). It implies tnat to understand CPV in this minimal SO(10) model, one must have a non-CKM source for CPV So it would be interesting to see how CPV can be generated in this model to explain ν masses and mixings, along with generation of BAU through Leptogenesis with the minimal modification. Attempts have already been made in this direction [23,24], but they included 120-dim Higgs and CP is violated through complex Yukawa couplings.

In the present work, we propose a different scenario We show that if assume SCPV at higher scales in minimal SUSY SO(10) theory (with 10+126 Higgs) with complex VEV for B-L breaking 126 Higgs, one can't have a nontrivial CPV phase So we propose that if we include two 126 Higgs bosons, one with real VEV and the other with a complex VEV, one can have a nontrivial value of CPV phase by some fine-tuning in the Higgs coupling constants of the Lagrangian. Now since the theory has $SU(4)_C$ symmetry at higher scales, the CKM phase in the baryonic quark mass matrix will be related to CP phases in the leptonic sector as well And since heavy RH majorana neutrino mass matrix will be complex (due to complex VEV on 126 Higgs) the model has the potential to explain BAU also It should be noted that CPV may be generated, in general by assigning VEV of any Higgs to be complex. But advantage of 126 having complex VEV is that, it appears in mass relations of fermions, to correct them, through induced VEV of triplet of 126 So it can directly generate CKM-CP violation in the quark sector and leptonic sector We would like to stress that we are not attempting to comment on other issues such as strong CP, SUSY CP problems *etc*, which can be solved may be by imposing some additional symmetries on the Lagrangian, or *via* some other mechanism This lies beyond the scope of this paper.

Now, we would like to present the distinguishing features and novelties of our work, as compared to some of the recent works in this line:

1. In [23,24], CP is introduced through complex Yukawa couplings, whereas we use SCPV.
2. In [9], SUSY SO(10) → SM *via* intermediate SU(5), while here we have used $SU(2)_L \times SU(2)_R \times SU(4)_C$ as the intermediate symmetry, although the breaking is single step (*i.e.* $M_U = M_R$ [17])
3. In [8], they add extra Higgs/Higgs+fermions to the SM, while here we have added extra 126 Higgs to the SUSY SO(10) theory, with VEV of one of the 126 as real, and that of the other as complex. At the same time, we propose that it be applied for specific model building purpose (for neutrino masses).

3. The model

We consider the SUSY SO(10) theory, with 45(A) + 54(S) dim Higgs field breaking SO(10) down to the L-R symmetric group $SU(2)_L \times SU(2)_R \times U(1)_{(B\text{-}L)} \times SU(4)_C$ (G_{2213}), and the minimal Higgs set $10 + 126 + \overline{126}$ that couple to matter and also break the G_{2213} group to G_{31} $SU(3)_C \times U(1)_{em}$) [17] (these details are well established, but for the sake of completeness, we shall review them briefly here). The Majorana mass of heavy RH neutrino owes its origin to the breaking of local B-L symmetry, therefore $M_R \sim M_{seesaw} \sim M_{B\text{-}L}$ [25] Local B-L symmetry provides a natural way to understand smallness of RH neutrino mass compared to M_{pl} . With G_{2213} one can understand parity violation in nature. 126 (Δ) leaves R-parity as an exact symmetry, and explains why neutralino can act as stable dark matter component [26]. In a generic SO(10) with 126 getting VEV, one gets two contributions to masses – type-I see-saw and type-II see-saw (from induced VEV of the triplet of 126 Higgs). The superpotential also contains Planck scale induced non-renormalizable terms (more than dim-3), to give induced VEV to triplet of 126 (for type-II see-saw). If these are not included, 210 Higgs is needed, but getting DTS is not very simple [27] here. The superpotential of the theory contains three parts,

$$W = W_f + W_s + W_p, \; W_f = h_{ab}\Psi_a\Psi_b H + f_{ab}\Psi_a\Psi_b\bar{\Delta} \tag{1}$$

where, W_f generates mass of matter, with (2,2,1) of 10 dim H and (2,2,15) of 126 dim Higgs acquiring VEV. The W_s contains scalar Higgs contribution, and is

$$W_s = (\mu_H + \lambda S)HH + \mu_s S^2 + \lambda_s S^3 + \mu_A A^2 + \mu_\Delta \Delta\bar{\Delta} + \lambda_\Delta \Delta A\bar{\Delta} + \lambda_s'\left(S\Delta\Delta + S\Delta\bar{\Delta}\right) + \lambda_A S A^2 \tag{2}$$

The W_P is planck-scale induced part of the superpotential

$$W_P = \frac{\sqrt{8\pi}}{M_{Pl}}\lambda_P \Delta A^2 H \, . \tag{3}$$

Now from the superpotential, the F-term (Higgs part) of the potential can be constructed as $V = \sum_i \left|\frac{\partial W}{\partial \sigma}\right|^2$ where σ 's are the Higgs scalars,

$$V = \left|\frac{\partial W}{\partial \Delta}\right|^2 + \left|\frac{\partial W}{\partial \bar{\Delta}}\right|^2 + \left|\frac{\partial W}{\partial S}\right|^2 + \left|\frac{\partial W}{\partial A}\right|^2 + D - term \tag{4}$$

and it is easy to see that $< A > \Delta\bar{\Delta}H$ term from $\left|\frac{\partial W}{\partial \Delta}\right|^2$ will contribute induced VEV to Σ (2, 2, 15) of 126 Higgs, to correct mass relations of fermions, while $\Delta\Delta\, HH$ from $\left|\frac{\partial W}{\partial S}\right|^2$ term will contribute induced VEV to triplet $\Delta_L\left(3,1,\overline{10}\right)$ for type-II see-saw mechanism.

Next, we shall consider how the breakings of higher symmetries is realized through VEVs of Higgs along different directions. In a SUSY theory, the ground state should have zero energy, so both F-flatness and D-flatness conditions must be satisfied. The latter is ensured by the presence of both Σ and $\bar{\Sigma}$ The F-flatness conditions, with the scalars acquiring VEVs as follows are ·

$$< S >= diag(k,k,k,k,k,k,k',k',k',k'),\ < A >= i\tau_2 \times diag(b\ b,b,c,c) \tag{5}$$

$$< \Delta >= v_R e^{i\alpha},\ < \bar{\Delta} >= v_R e^{-i\alpha}, \tag{6}$$

$$F_s \cdot \frac{\partial W}{\partial k} = 2\mu_s k + 3\lambda_s k^2 + \lambda_s'\left(x_0 v_R^2 e^{2i\alpha} + x_0 v_R^2 e^{-2i\alpha}\right) - \lambda_A b^2 = 0 \tag{7}$$

$$\frac{\partial W}{\partial k'} = 2\mu_s k' + 3\lambda_s k'^2 + \lambda_s'\left(v_R^2 e^{2i\alpha} + v_R^2 e^{-2i\alpha}\right) - \lambda_A c^2 = 0 \tag{8}$$

$$F_A \ \frac{\partial W}{\partial b} = -2b\mu_A + \lambda_\Delta x_0 v_R^2 - 2b\lambda_A k = 0 \tag{9}$$

$$\frac{\partial W}{\partial c} = -2c\mu_A + \lambda_\Delta v_R^2 - 2c\lambda_A k' = 0 \tag{10}$$

$$F_\Delta = \mu_\Delta v_R e^{-i\alpha} + \lambda_\Delta (x_0 b + c) v_R e^{-i\alpha} + 2\lambda_s'(y_0 k + k') v_R e^{i\alpha} = 0 \tag{11}$$

$$F_{\bar{\Delta}} = \mu_\Delta v_R e^{i\alpha} + \lambda_\Delta (x_0 b + c) v_R e^{i\alpha} + 2\lambda_s' (y_0 k + k') v_R e^{-i\alpha} = 0 \tag{12}$$

where x_0 and y_0 are appropriate C-G coefficients, due to involvements of different groups These constraints must give a non-trivial solution for the CPV phase. The F_Δ and $F_{\bar{\Delta}}$ constraints can be written as

$$(A+B)\cos\alpha + i(A-B)\sin\alpha = 0 \tag{13}$$

$$(A+B)\cos\alpha + i(B-A)\sin\alpha = 0 \tag{14}$$

where constants A and B involve various Higgs couplings and VEVs etc It is easy to see that these equations give only the trivial solutions $\alpha = 0$ and $\alpha = \pi/2$ These values of α have also to be satisfied simultaneously by the F_s constraints,

$$F_{s_k} : \cos 2\alpha = \frac{\lambda_A b^2 - 2\mu_s k + 3\lambda_s k^2}{2\lambda_s' x_0 v_R^2} \tag{15}$$

$$F_{s_k} : \cos 2\alpha = \frac{\lambda_A c^2 - 2\mu_s k' + 3\lambda_s k'^2}{2\lambda_s' v_R^2} \tag{16}$$

Eqs (13-16) are the new results of our present work, which implies that one can't have a nontrivial value of the CPV phase in a L-R symmetric minimal SUSY SO(10) theory, where CP has been broken spontaneously at high scale by the complex VEV of 126 Higgs.

4. New proposal

To overcome this difficulty, therefore, we propose that in the model, we have two 126 Higgses, Δ_1 and Δ_2, such that one of them acquires a real VEV while the other one a complex VEV,

$$< \Delta_1 >= v_R e^{-i\alpha}, \quad < \Delta_2 >= \varepsilon\, v_R \tag{17}$$

here ε is a fine tuning parameter, which can be adjusted to get a desired nontrivial value of CPV phase at higher scales (see Eqs (15-17)) Note that this is not possible in a theory with one Higgs (126), or with two 126s with same VEVs (real or complex) The part of the new superpotential generating fermion masses will look like,

$$W_f = h_{ab}\Psi_a\Psi_b + f_{1ab}\Psi_a\Psi_b\overline{\Delta}_1 + f_{2ab}\Psi_a\Psi_b\overline{\Delta}_2\,. \tag{18}$$

Since the VEV of a 126 Higgs is complex, the fermion mass matrices as well as the heavy right handed majorana mass matrix will be complex There will be now new relations among fermion masses, with a new parameter ε in the theory (the theory is *quasi-minimal* in that sense), and a new type-II see-saw formula The fitting of femion masses including neutrino masses at GUT scale according to these new relations can be done This analysis is going to be very involved and can be taken up in future works We would like to point out that since VEV of the 126 Higgs occurs in the masses of quarks as well, we have CKM-CP violation as well in the theory So, the CKM-CP violation as well as CPV in the neutrino masses is the manifestation of SCPV at higher scales, since VEV of 126 Higgs which is complex, is ~M_{GUT}.

5. Discussion and conclusion

To conclude, we have presented a novel mechanism of generating CP spontaneously at higher scales in a L-R symmetric SUSY SO(10) theory, which can be further applied in context of neutrino masses and mixings, and leptogenesis. Eq. (17) is the new idea proposed here for the first time, in this work, which together with Eqs similar to (13-16) can give a nontrivial CP violating phase (other than 0 or $\pi/2$) in this quasi-minimal theory. The numerical analyses of fermion masses using GUTs and CKM phase is available in literature [14, 20, 21, 22] , but here we have addressed a more fundamental question - if CPV phase is at all allowed in a grand unified theory by the potential? Of course further investigations, as far as its applications and implications of this idea are concerned, are needed, which can be taken up in future works.

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