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Bosonic seesaw mechanism in a classically conformal extension of the Standard Model

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ABSTRACT

We suggest the so-called bosonic seesaw mechanism in the context of a classically conformal $U(1)_{B-L}$ extension of the Standard Model with two Higgs doublet fields. The $U(1)_{B-L}$ symmetry is radiatively broken via the Coleman–Weinberg mechanism, which also generates the mass terms for the two Higgs doublets through quartic Higgs couplings. Their masses are all positive but, nevertheless, the electroweak symmetry breaking is realized by the bosonic seesaw mechanism. Analyzing the renormalization group evolutions for all model couplings, we find that a large hierarchy among the quartic Higgs couplings, which is crucial for the bosonic seesaw mechanism to work, is dramatically reduced toward high energies. Therefore, the bosonic seesaw is naturally realized with only a mild hierarchy, if some fundamental theory, which provides the origin of the classically conformal invariance, completes our model at some high energy, for example, the Planck scale. We identify the regions of model parameters which satisfy the perturbativity of the running couplings and the electroweak vacuum stability as well as the naturalness of the electroweak scale.

In the Standard Model (SM), the electroweak symmetry breaking is realized by the negative mass term in the Higgs potential, which seems to be artificial because there is nothing to stabilize the electroweak scale. If new physics takes place at a very high energy, e.g. the Planck scale, the mass term receives large corrections which are quadratically sensitive to the new physics scale, so that the electroweak scale is not stable against the corrections. This is the so-called gauge hierarchy problem. It is well known that supersymmetry (SUSY) can solve this problem. Since the mass corrections are completely canceled by the SUSY partners, no fine-tuning is necessary to reproduce the electroweak scale correctly, unless the SUSY breaking scale is much higher than the electroweak scale. On the other hand, since no indication of SUSY particles has been obtained in the large hadron collider (LHC) experiments, one may consider other solutions to the gauge hierarchy problem without SUSY.

In this direction, recently a lot of works have been done in models based on a classically conformal symmetry. There are $U(1)$ gauge extension [1–23], and non-Abelian gauge extension, in which conformal symmetry is broken by radiative corrections [15,24–28] and strong dynamics [29–37]. In addition, there are also non-gauge extended models [see Ref. [38] and therein].[1] This direction is based on the argument by Bardeen [39] that the quadratic divergence in the Higgs mass corrections can be subtracted by a boundary condition of some ultraviolet complete theory, which is classically conformal, and only logarithmic divergences should be considered (see Ref. [6] for more detailed discussions). If this is the case, imposing the classically conformal symmetry to the theory is another way to solve the gauge hierarchy problem. Since there is no dimensionful parameter in this class of models, the classically conformal symmetry must be broken by quantum corrections. This structure fits the model first proposed by Coleman and Weinberg [40], where a model is defined as a massless theory and the classically conformal symmetry is radiatively broken by the Coleman–Weinberg (CW) mechanism, generating a mass scale through the dimensional transmutation.

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[1] In Ref. [38], the upper bound on the mass of the lightest additional scalar boson is obtained as $\simeq 543$ GeV, which is independent of its isospin and hypercharge. Thus, the classically conformal model is strongly constrained without gauge extension.

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In this paper we propose a classically conformal $U(1)_{B-L}$ extended SM with two Higgs doublets. An SM singlet, $B-L$ Higgs field develops its vacuum expectation value (VEV) by the CW mechanism, and the $U(1)_{B-L}$ symmetry is radiatively broken. This gauge symmetry breaking also generates the mass terms for the two Higgs doublets through quartic couplings between the two Higgs doublets and the $B-L$ Higgs field. We assume the quartic couplings to be all positive at the $U(1)_{B-L}$ breaking scale but, nevertheless, the electroweak symmetry breaking is triggered through the so-called bosonic seesaw mechanism [41–43], which is analogous to the seesaw mechanism for the neutrino mass generation and leads to a negative mass squared for the SM-like Higgs doublet. Because a negative quartic coupling may cause vacuum instability, it is important to take all quartic couplings to be positive, while in the conventional models, e.g., Refs. [3] and [29], the mixing coupling between the $SU(2)_L$ doublet and singlet fields is necessarily negative to realize the negative mass term of the SM-like Higgs doublet. Our model guarantees that the mixing couplings are positive at the breaking scale with a hierarchy among the quartic couplings, which successfully derives the bosonic seesaw mechanism. The hierarchy seems to be unnatural, but we find that the renormalization group evolutions of the quartic couplings dramatically reduce the large hierarchy toward high energies. On the other hand, a large hierarchy exists even in the conventional model, that is, the mixing coupling should be much small as $(\text{EW scale})^2/v^2$ with a conformal symmetry breaking scale v, except for $v \sim \mathcal{O}(1)$ TeV. Note that the degree of the hierarchy in our model does not increase as the symmetry breaking scale becomes larger.

In the following, let us explain our model in detail. We consider an extension of the SM with an additional $U(1)_{B-L}$ gauge symmetry. Our model has three scalar fields, that is, two Higgs doublets (H_1 and H_2) and one SM singlet, $B-L$ Higgs field (Φ) are introduced. The $U(1)_{B-L}$ charges of H_1, H_2, and Φ are 0, 4, and 2, respectively. As is well known, the introduction of the three right-handed neutrinos (N^i, $i=1,2,3$) with a $U(1)_{B-L}$ charge is crucial to make the model free from all the gauge and gravitational anomalies. In addition, we impose a classically conformal symmetry to the model, under which the scalar potential is given by

$$\begin{aligned} V &= \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\ &\quad + \lambda_4(H_2^\dagger H_1)(H_1^\dagger H_2) + \lambda_\Phi|\Phi|^4 + \lambda_{H1\Phi}|H_1|^2|\Phi|^2 \\ &\quad + \lambda_{H2\Phi}|H_2|^2|\Phi|^2 + \left(\lambda_{\rm mix}(H_2^\dagger H_1)\Phi^2 + h.c.\right). \end{aligned} \tag{1}$$

Here, all of the dimensionful parameters are prohibited by the classically conformal symmetry. In this system, the $U(1)_{B-L}$ symmetry must be radiatively broken by quantum effects, i.e., the CW mechanism. The CW potential for Φ is described as

$$V_\Phi(\phi) = \frac{1}{4}\lambda_\Phi(v_\Phi)\phi^4 + \frac{1}{8}\beta_{\lambda_\Phi}(v_\Phi)\phi^4\left(\ln\frac{\phi^2}{v_\Phi^2} - \frac{25}{6}\right), \tag{2}$$

where $\Re[\Phi] = \phi/\sqrt{2}$, and $v_\Phi = \langle\phi\rangle$ is the VEV of Φ. When the beta function β_{λ_Φ} is dominated by the $U(1)_{B-L}$ gauge coupling (g_{B-L}) and the Majorana Yukawa couplings of right-handed neutrinos (Y_M), the minimization condition of V_Φ approximately leads to

$$\lambda_\Phi \simeq \frac{11}{6\pi^2}\left(6g_{B-L}^4 - {\rm tr}Y_M^4\right), \tag{3}$$

where all parameters are evaluated at v_Φ. Through the $U(1)_{B-L}$ symmetry breaking, the mass terms of the two Higgs doublets arise from the mixing terms between $H_{1,2}$ and Φ, and the scalar mass squared matrix is read as

$$\begin{aligned} -\mathcal{L} &= \frac{1}{2}(H_1, H_2)\begin{pmatrix} \lambda_{H1\Phi}v_\Phi^2 & \lambda_{\rm mix}v_\Phi^2 \\ \lambda_{\rm mix}v_\Phi^2 & \lambda_{H2\Phi}v_\Phi^2 \end{pmatrix}\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \\ &\approx \frac{1}{2}(H_1', H_2')\begin{pmatrix} \lambda_{H1\Phi}v_\Phi^2 - \frac{\lambda_{\rm mix}^2 v_\Phi^2}{\lambda_{H2\Phi}} & 0 \\ 0 & \lambda_{H2\Phi}v_\Phi^2 \end{pmatrix}\begin{pmatrix} H_1' \\ H_2' \end{pmatrix}, \end{aligned} \tag{4}$$

where H_1' and H_2' are mass eigenstates, and we have assumed a hierarchy among the quartic couplings as $0 \le \lambda_{H1\Phi} \ll \lambda_{\rm mix} \ll \lambda_{H2\Phi}$ at the scale $\mu = v_\Phi$. In the next section, we will show that this hierarchy is dramatically reduced toward high energies in their renormalization group evolutions. Because of this hierarchy, mass eigenstates H_1' and H_2' are almost composed of H_1 and H_2, respectively. Hence, we approximately identify H_1' with the SM-like Higgs doublet. Note that even though all quartic couplings are positive, the SM-like Higgs doublet obtains a negative mass squared for $\lambda_{H1\Phi} \ll \lambda_{\rm mix}^2/\lambda_{H2\Phi}$, and hence the electroweak symmetry is broken. This is the so-called bosonic seesaw mechanism [41–43].

In more precise analysis for the electroweak symmetry breaking, we take into account a scalar one-loop diagram through the quartic couplings, λ_3 and λ_4, and the SM-like Higgs doublet mass is given by

$$m_h^2 \simeq \lambda_{H2\Phi}v_\Phi^2\left[\frac{1}{2}\left(\frac{\lambda_{\rm mix}}{\lambda_{H2\Phi}}\right)^2 + \frac{2\lambda_3+\lambda_4}{16\pi^2}\right], \tag{5}$$

where we have omitted the $\lambda_{H1\Phi}$ term in the second line, and the observed Higgs boson mass $M_h = 125$ GeV is given by $M_h = m_h/\sqrt{2}$.

In addition to the scalar one-loop diagram, one may consider other Higgs mass corrections coming from a neutrino one-loop diagram and two-loop diagrams involving the $U(1)_{B-L}$ gauge boson (Z') and the top Yukawa coupling, which are, respectively, found to be [3]

$$\delta m_h^2 \sim \frac{Y_\nu^2 Y_M^2 v_\Phi^2}{16\pi^2}, \qquad \delta m_h^2 \sim \frac{y_t^2 g_{B-L}^4 v_\Phi^2}{(16\pi^2)^2}, \tag{6}$$

where Y_ν and y_t are Dirac Yukawa couplings of neutrino and top quark, respectively. It turns out that these contributions are negligibly small compared to the scalar one-loop correction in Eq. (5). As we will discuss in the next section, the quartic couplings λ_3 and λ_4 should be sizable $\lambda_{3,4} \gtrsim 0.15$ in order to stabilize the electroweak vacuum. The neutrino one-loop correction is roughly proportional to the active neutrino mass by using the seesaw relation, and it is highly suppressed by the lightness of the neutrino mass. The two-loop corrections with the Z' boson are suppressed by a two-loop factor $1/(16\pi^2)^2$. Unless g_{B-L} is large, the two-loop corrections are smaller than the scalar one-loop correction.

The other scalar masses are approximately given by

$$M_\phi^2 = \frac{6}{11}\lambda_\Phi v_\Phi^2, \tag{7}$$

$$M_H^2 = M_A^2 = \lambda_{H2\Phi}v_\Phi^2 + (\lambda_3+\lambda_4)v_H^2, \tag{8}$$

$$M_{H^\pm}^2 = \lambda_{H2\Phi}v_\Phi^2 + \lambda_3 v_H^2, \tag{9}$$

where M_ϕ is the mass of the SM singlet scalar, M_H (M_A) is the mass of CP-even (CP-odd) neutral Higgs boson, and $M_{H\pm}$ is the mass of charged Higgs boson. The extra heavy Higgs bosons are almost degenerate in mass. The masses of the Z' boson and the right-handed neutrinos are given by

$$M_{Z'} = 2g_{B-L}v_\Phi, \tag{10}$$

$$M_N = \sqrt{2}y_M v_\Phi \simeq \left[\frac{3}{2N_\nu}\left(1 - \frac{\pi^2\lambda_\Phi}{11g_{B-L}^4}\right)\right]^{1/4} M_{Z'}, \tag{11}$$