Decoupling of Parity- and $SU(2)_R$-Breaking Scales: A New Approach to Left-Right Symmetric Models

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A new approach to left-right symmetric models is proposed, where the left-right discrete-symmetry- and $SU(2)_R$-breaking scales are decoupled from each other. This changes the spectrum of physical Higgs bosons which leads to different patterns for gauge hierarchies in $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$ and SO(10) models. Most interesting are two SO(10) symmetry-breaking chains with an intermediate $U(1)_R$ symmetry. These are such as to provide new motivation to search for $\Delta B = 2$ and right-handed current effects at low energies.

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Left-right symmetric models[1] based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ have been the focus of a great deal of attention during past years as a possible new symmetry of weak interaction beyond the standard $SU(2)_L \otimes U(1)$ electroweak model. A central question in these models is the scale of left-right discrete symmetry breaking. This new scale is conventionally associated with the breaking of the $SU(2)_R \otimes U(1)_{B-L}$ gauge symmetry down to $U(1)_Y$ of the standard model. SO(10) grand-unified embedding of these models is known[2] to lead to a high scale for M_R ($M_R \sim 10^{12}$ GeV) for $\sin^2\theta_w \simeq 0.23$–$0.24$. Similar results are also obtained for $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$ unification. Thus within the framework of grand or partial unified models any possible effects due to right-handed currents would be highly suppressed. In this note, we propose an alternative scenario where the breaking scales of discrete left-right symmetry and the local $SU(2)_R$ symmetry are decoupled, giving rise to a new scale M_D, distinct from the mass of the right-handed gauge bosons, M_{W_R}.

The original symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes P$ (where P denotes a left-right discrete symmetry)[1,3] is first broken down to $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ at a mass scale M_P. This manifests itself in different values of g_L and g_R as well as a different spectrum of Higgs boson masses and not in a nonzero W_R mass as in the left-right models discussed to date.[1] The $SU(2)_R$ gauge symmetry is subsequently broken down at a mass scale $M_{W_R} << M_P$. The above asymmetry in the Higgs boson mass spectrum changes the behavior of gauge coupling constants, once this model is embedded in grand unified theories (GUT's). It is this decoupling of parity and $SU(2)_R$ gauge-symmetry breaking and its impact on low-energy predictions of grand unified models that we study in this paper.

We find that our approach leads to a more hopeful scenario for detecting the effects of right-handed currents at low energies within the framework of partial unified $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$ and SO(10) GUT's without arbitrary fine tuning of parameters. In the context of the first model, with $\sin^2\theta_w \simeq 0.23 \pm 0.01$,[4] we obtain an $SU(4)_C$ breaking scale of order 10^8 GeV, whereas in the SO(10) model, we have isolated two scenarios with $SU(2)_R$ and $U(1)_R$ as intermediate symmetries.[5] In one case, we obtain both charged and neutral right-handed gauge-boson masses in the 1–5-TeV range whereas in the other the $SU(4)_C$-breaking scale is of order 10^6 GeV for $\alpha_s(M_W) \simeq 0.1$–0.12 and $\sin^2\theta_w \simeq 0.22$–$0.245$. In the first case, many lepton-number–nonconserving processes[6] will become observable whereas in the second case N-$\bar{N}$ oscillation becomes accessible to planned experiments.[7]

Within the framework of our discussions, we can have M_P and M_{W_R} completely independent at the tree level or $SU(2)_R$-symmetry breaking may be triggered by breaking of the discrete symmetry. The advantage of the second alternative is that new physics can appear by only one fine tuning of parameters needed to generate the mass hierarchy between M_P and M_{W_R}.

We now present an explicit realization of our idea using the Higgs potential for an $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes P$ model. To avoid repetition of existing literature, we omit any discussion of the fermionic sector[1] here. To implement the symmetry-breaking pattern

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes P \rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \rightarrow SU(2)_L \otimes U(1),$$

we choose the Higgs multiplets with their group transformation properties denoted within the parentheses:

$\Delta_L(3,1,2)$, $\Delta_R(1,3,2)$, $\phi(2,2,0)$, and $\eta(1,1,0)$, with the following transformation properties under parity[1,2]:

$$\Delta_L \leftrightarrow \Delta_R;\quad \phi \leftrightarrow \phi^\dagger;\quad \eta \rightarrow -\eta. \tag{1}$$

The most general renormalizable Higgs potential involving these fields can be written as

$$V = V_\Delta + V_\phi + V_\eta + V_{\eta\Delta} + V_{\Delta\phi} + V_{\eta\phi}, \tag{2}$$

$$V_\Delta = \mu_\Delta^2\{\mathrm{Tr}(\Delta_L^\dagger \Delta_L) + L \rightarrow R\} + \text{quartic terms}, \tag{3}$$

$$V_\eta = -\mu_\eta^2 \eta^2 + \lambda_1 \eta^4, \tag{4}$$

$$V_{\eta\Delta} = M\eta(\Delta_L^\dagger\Delta_L - \Delta_R^\dagger\Delta_R) + \lambda_2\eta^2(\Delta_L^\dagger\Delta_L + \Delta_R^\dagger\Delta_R). \tag{5}$$

Here V_ϕ and $V_{\Delta\phi}$ are also chosen in the most general manner so as to lead to $\langle\phi\rangle \neq 0$ that breaks $SU(2)_L \otimes U(1)$ symmetry.[1] It is clear from Eq. (4) that for $\mu_\eta^2 > 0$, the minimum of the potential is at $\langle\eta\rangle \equiv M_P = \mu_\eta/(2\lambda_1)^{1/2}$ which breaks parity symmetry without breaking gauged $SU(2)_R$ symmetry. Eqs. (5) and (3) then imply

$$\mu_{\Delta_L}^2 = \mu_\Delta^2 + M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2,$$
$$\mu_{\Delta_R}^2 = \mu_\Delta^2 - M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2. \tag{6}$$

At this stage, we impose the fine-tuning condition in Eq. (6) such that $\mu_{\Delta_R}^2 < 0$ and $|\mu_{\Delta_R}^2| \ll \langle\eta\rangle^2$. This leads to a minimum of the potential where $\langle\Delta_R^0\rangle = V_R \neq 0$. Thus, the $SU(2)_R$-breaking scale is induced by the parity-breaking scale. We note that the masses of the components of Δ_R are of order V_R whereas the masses of the components of Δ_L are of order $\langle\eta\rangle$. The spectrum of Higgs bosons exhibits the left-right asymmetry even though $SU(2)_R$ symmetry is unbroken.

Among the parameters that reflect the left-right asymmetry above the $SU(2)_R$-breaking scale is the ratio $g_R/g_L \equiv \delta$. For $\mu \gg \langle\eta\rangle$, parity symmetry is exact and $\delta = 1$, but for $V_R < \mu < M_P$ we get

$$\delta^{-2} = 1 + \frac{\frac{2}{3}\alpha(M_{W_R})N_\Delta}{2\pi\sin^2\theta_w(M_{W_R})}\ln\left(\frac{M_P}{M_{W_R}}\right). \tag{7}$$

Here, N_Δ is the number of complex $SU(2)_R$ triplets. For a small number of Higgs multiplets, however, the variation of δ from its symmetric value is quite limited.

We now consider the partial unified model based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C \otimes P$ ($\equiv G_{1D}$) with the following pattern of symmetry breaking:

$$G_{1D} \xrightarrow{M_P} G_1 \xrightarrow{M_c} G_{123},$$

where $G_1 = SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$, $G_{123} = U(1) \otimes SU(2)_L \otimes SU(3)_C$, and the subscript D is used when P is a good symmetry. The effect of the P-symmetry breaking here is to lift the multiplet $\Delta_L(3,1,10)$ to the mass $M_P \gg M_c = M_{W_R}$, thus forcing it to decouple from the evolution of coupling constants below M_P,

$$\sin^2\theta_w(M_W) = \frac{1}{2} - \frac{1}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)} - \frac{\alpha(M_W)}{4\pi}\left[\frac{20}{3}\ln\frac{M_P}{M_{W_R}} + \frac{44}{3}\ln\frac{M_{W_R}}{M_W}\right]. \tag{8}$$

This implies that for $\sin^2\theta_w \simeq 0.24$, and $\alpha_s(M_W) \simeq 0.1$, $M_P \simeq 10^{19}$ GeV yields $M_{W_R} = M_c \simeq 10^8$ GeV. Thus, the entire $\Delta_R(1,3,10)$ multiplet has mass $\approx \lambda M_{W_R} \simeq 10^7$ GeV consistent with the minimal fine tuning.[8] Since the $\Delta_{qq}(1,3,6)$ members of this multiplet contribute to N-$\bar{N}$ oscillation, we get $A_{\Delta B=2} \simeq 10^{36}$ $(\mathrm{GeV})^{-5}$ or $\tau_{N\text{-}\bar{N}} \approx 10^{14}$ sec.

We now proceed to discuss the realization of our idea in the context of an SO(10) GUT. An element of the SO(10) group (called D parity) behaves in a very similar manner to parity. Under this discrete symmetry, for example, u_L transforms into $(u^c)_L \equiv i\sigma_2 u_R^*$. The operator can be written as $D \equiv \sigma_{67} \times \sigma_{23}$ in the convention of Mohapatra and Sakita[9] and of Kibble, Lazarides, and Shafi.[9] In general, this discrete symmetry is not the same as parity or charge-conjugation operations. However, when all Higgs couplings are real, it can be identified with parity. In any case, in an SO(10) model, D-parity breaking (the corresponding scale also denoted by M_P) as we discuss here still leads to parity nonconservation at low energies (such as different couplings for left- and right-handed weak interaction, etc.). In order to implement our idea, we need an irreducible multiplet of SO(10), which contains an $SU(2)_L \otimes SU(2)_R \otimes SU(4)$ singlet field which is odd under D parity. The smallest representation that contains such a field is the 210-dimensional Higgs multiplet which is the totally antisymmetric fourth-rank tensor Φ_{abcd} where $a,b,c,d = 1,\ldots, 10$. In the convention where $a,b,\ldots = 1,\ldots,6$ denote the SO(6) subgroup [or $SU(4)_C$] and $a,b,\ldots = 7,\ldots,10$ denote the SO(4) or $SU(2)_L \otimes SU(2)_R$ subgroup, the D-parity odd singlet we are seeking is given by the component Φ_{78910}. Note also that the neutral component of the (1,1,15) multiplet of G_1 is L-R odd (even) in the representation 45 (210) of SO(10).

We consider the following symmetry-breaking chains:

$$\mathrm{SO}(10) \underset{\{210\}}{\overset{M_u}{\longrightarrow}} G_1 \underset{\{126\}}{\overset{M_R}{\longrightarrow}} G_{123}, \tag{i}$$

$$\mathrm{SO}(10) \underset{\{210\}}{\overset{M_u}{\longrightarrow}} G_{2D} \underset{\{210\}}{\overset{M_P}{\longrightarrow}} G_2 \underset{\{210\}'}{\overset{M_{R^+}}{\longrightarrow}} G_3 \underset{\{126\}}{\overset{M_{R^0}}{\longrightarrow}} G_{123}, \tag{ii}$$

$$\mathrm{SO}(10) \underset{\{54\}}{\overset{M_u}{\longrightarrow}} G_{1D} \underset{\{210\}}{\overset{M_P}{\longrightarrow}} G_1 \underset{\{210\}}{\overset{M_c}{\longrightarrow}} G_3 \underset{\{126\}}{\overset{M_{R^0}}{\longrightarrow}} G_{123}, \tag{iii}$$

where

$$G_2 = SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes SU(3)_C, \quad G_3 = SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \otimes SU(3)_C.$$

The multiplets in curly brackets are responsible for symmetry breaking at the respective stages. Common to all these scenarios is the feature that between M_P and M_R, only the right-handed Higgs bosons (in our case triplets) contribute to the β functions and not the left-handed ones. This has a profound effect on the mass hierarchies. Below, we give the equations for $\sin^2\theta_w$ and α_s, for each of the three cases:

$$\sin^2\theta_w(M_W) = \frac{3}{8} - \frac{3\alpha(M_W)}{16\pi} f_i(M_u, M_P, \ldots, M_W), \tag{9}$$

$$\frac{\alpha(M_W)}{\alpha_s(M_W)} = \frac{3}{8} - \frac{3\alpha(M_W)}{16\pi} h_i(M_u, M_P, \ldots, M_W). \tag{10}$$

Here f_i and h_i are functions of mass scales and are given below for the three cases $i = 1,2,3$ under consideration, where Higgs boson masses are taken in accordance with the minimal fine-tuning hypothesis of Ref. 8. For case (i),

$$f_1 = \frac{86}{9}\ln\frac{M_u}{M_c} + \frac{109}{9}\ln\frac{M_c}{M_u} + \frac{109}{9}\ln\frac{M_c}{M_W}, \tag{11a}$$

$$h_1 = -2\ln\frac{M_u}{M_c} + \frac{67}{3}\ln\frac{M_c}{M_W}; \tag{11b}$$

for case (ii),

$$f_2 = 6\ln\frac{M_u}{M_P} + \frac{20}{3}\ln\frac{M_P}{M_{W_R}} + \frac{115}{9}\ln\frac{M_{W_R}}{M_{Z_R}} + \frac{109}{9}\ln\frac{M_{Z_R}}{M_W}, \tag{11c}$$

$$h_2 = \frac{58}{3}\ln\frac{M_u}{M_P} + \frac{52}{3}\ln\frac{M_P}{M_{W_R}} + 23\ln\frac{M_{W_R}}{M_{Z_R^0}} + \frac{67}{3}\ln\frac{M_Z}{M_W}; \tag{11d}$$

for case (iii),

$$f_3 = -\frac{56}{9}\ln\frac{M_u}{M_P} + \frac{89}{9}\ln\frac{M_P}{M_c} + \frac{115}{9}\ln\frac{M_c}{M_{Z_R}} + \frac{109}{9}\ln\frac{M_{Z_R}}{M_W}, \tag{11e}$$

$$h_3 = \frac{56}{3}\ln\frac{M_u}{M_P} + 17\ln\frac{M_P}{M_c} + 23\ln\frac{M_c}{M_{Z_R}} + \frac{67}{3}\ln\frac{M_{Z_R}}{M_W}. \tag{11f}$$

For case (i) we find, for $\alpha_s(m_W) \simeq 0.1$ and $\sin^2\theta_w = 0.24$, $M_c \geqslant 10^{12}$ GeV for $M_u \leqslant 10^{19}$ GeV. No interesting low-energy physics appears in this case. For case (ii) we find for $M_u \simeq M_P \approx 2\times 10^{18}$ GeV that both M_{W_R} and M_Z can be as low as 1–5 TeV with $\sin^2\theta_w \simeq 0.245$ and $\alpha_s(M_W) \simeq 0.12$. This is clearly of a great deal of interest in connection with both detection of "live" right-handed gauge bosons as well as other low-energy $\Delta L \neq 0$ processes. The values of $\sin^2\theta_w$ can be reduced to 0.225, with $\alpha_s \simeq 0.1$ if the G_{2D} is replaced by G_1 in chain (ii). For case (iii), for $\sin^2\theta_w = 0.23$ and $\alpha_s(M_W) \simeq 0.1$, $M_u \simeq 20 M_P \approx 2\times 10^{17}$ GeV; $M_c = M_{W_R^\pm} \simeq 10^5$ GeV with $M_{Z_R} \simeq 500$ GeV. This case can lead to N-$\bar{N}$ mixing times of order 10^7–10^8 sec. To our knowledge, this is the only nonsupersymmetric grand unified model[10] where N-$\bar{N}$ oscillation is naturally within observable range of present experiments.

To summarize, we propose a new approach to left-right symmetric models of weak interactions where the left-right discrete-symmetry- and $SU(2)_R$-breaking scales are different,[11] though one induces the other. Embedding this idea into SO(10) models, we find symmetry-breaking chains that can lead to low M_{W_R} as well as observable $\Delta B = 2$ transitions. Our findings should provide new impetus for the search for right-handed current effects both in the high- and low-energy regimes. Details of this analysis and other applications will be reported in a separate paper.

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[11]An alternative scenario for $g_L \neq g_R$ arises in an SU(16) model where $SU(16) \rightarrow SU(8)_L \times SU(8)_R$ with either SU(8) symmetry breaking down to $SU(2)\times SU(4)$ at a different mass scale from the other. This mechanism is different from the one proposed here. J. C. Pati, private communication.