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Left-Right Model of Electroweak Interaction with One Bidoublet and One Doublet Higgs Fields

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Abstract

We study the predictions of the left-right model of electroweak interaction based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group by using one bidoublet and one doublet Higgs fields. By choosing appropriate vacuum expectation values of Higgs fields, the low energy phenomenology of electroweak interaction can be understood. Leptons can acquire a mass via two scenarios, first via a Higgs mechanism with non-zero 'hypercharge-like' I in the Lagrangian density mass terms with the Yukawa couplings $G_l >> G_l^*$, and the second via a Higgs mechanism followed by a seesaw-like mechanism without the requirement that $G_l >> G_l^*$.

***Keywords**: Left-right model, Bidoublet and doublet Higgs fields, Lepton mass*

1 Introduction

Eventhough the Standard Model of electroweak interaction which is known as the Glashow-Weinberg-Salam (GWS) based on $SU(2)_L \otimes U(1)_Y$ gauge symmetry group has been succesful phenomenologically, it still far from a complete theory. The GWS model does not explain many fundamental problems such as the neutrino mass existence, and the origin of parity (*P*) violation in the weak interaction. Recent experimental data on atmospheric and solar neutrinos indicate strongly that neutrinos undergo oscillation which implies that the neutrinos have a tiny mass[1-7]. In order to extend the GWS model, many theories or models have been proposed.

One of the interesting models that can gives a mass to neutrinos and also can explains the origin of the parity violation in weak interaction is the left-right symmetry model based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group which is proposed by Senjanovic and Mohapatra[8]. Using two doublets Higgs fields, Senjanovic and Mohapatra found that the Higgs potential will be minimum when we choose the asymmetric solution to the doublet Higgs fields vacuum expectation values. Within this scheme, the presence of the spontaneous parity violation at low energy arises naturally, and the electroweak interaction based on $SU(2)_L \otimes U(1)_Y$ gauge symmetry group can be deduced from the left-right symmetry model which is based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$. Finally, the $SU(2)_L \otimes U(1)_Y$ gauge symmetry group breaks to $U(1)_{em}$ just like GWS model.

Introducing one additional bidoublet Higgs fields in order to generate fermions masses in their model, it is possible to obtain a small neutrino mass and two massive gauge bosons m_{W_L} and m_{W_R} with mass $m_{W_L} << m_{W_R}$ respectively. The spontaneous break-down of the parity in a class of gauge theories have also been investigated by Senjanovic[9]. Left-right model of quark and lepton masses without a scalar bidoublet has been proposed which predict a double seesaw mechanism for generating tiny neutrino mass[10]. But, left-right model without bidoublet Higgs leads to a non-renormalizable theory.

Any viable gauge model of electroweak interactions must give an answer to the two quite different problems: (i) the breaking of symmetry from the full gauge group into electromagnetic Abelian group $U(1)_{em}$ giving a mass to the gauge bosons and then explains the known structure of weak interactions, and (ii) the mass matrices for fermions[11]. Imposing the *O*(2) custodial symmetry with left and right Higgs fields are chosen as a doublet of *SU*(2), the known up-down structure of the doublet fermions masses, by insertion of ad hoc fermion-Higgs interactions, can be obtained[12]. Another model is the approximate custodial $SU(2)_{L+R}$ global symmetry[13]. But, the *O*(2) custodial symmetry leads to five dimensions operator in the mass term of Lagrangian density which lead to a non-renormalizable theory. A theory is renormalizable if the dimension of the operator in the Lagrangian density less than or equal to four[14,15]. Thus, the existence of the *O*(2) custodial symmetry in electroweak theory leads to a non-renormalizable theory. A left-right symmetry model with two Higgs bidoublet is also known to be a consistent model for both spontaneous *P* and *CP* violation[16]. The spontaneous *CP* phases and the flavour changing neutral currents in the left-right symmetry model also open the possibilty to obtain a large *CP* violation in the lepton sector as well as new Higgs bosons at the electroweak scale[17].

Motivated by the rich contents of left-right symmetry model, the experimental facts on neutrino mass existence, and also to anticipate the possibility to find new particles or gauge bosons in the LHC machine, in this paper we evaluate the predictive power of left-right model of electroweak interaction based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge symmetry with one bidoublet and one doublet Higgs fields. As far as we know, there is no paper using the left-right model of electroweak interaction by introducing one bidoublet and one doublet Higgs fields to break the symmetry. In this model, we put both left and right fermion fields to be an *SU*(2) doublet. In Section 2 we introduce explicitly our model and evaluate the minimum value of Higgs potential and bounded from below in order to justify our assumption in choosing the vacuum expectation values of the Higgs fields. In section 3, we evaluate the predictive power of the model on the gauge bosons and the leptons masses. In section 4, we discuss our results and its phenomenological aspects, and finally section 5 is devoted to a conclusion.

2. TheModel

We use the left-right model based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group with the following lepton fields assignment,

$$\psi_L = \begin{pmatrix} \nu_l \\ l_l^- \end{pmatrix}_L, \quad \psi_R = \begin{pmatrix} \nu_l \\ l_l^- \end{pmatrix}_R, \tag{1}$$

where $l = e, \mu, \tau$, and the bidoublet and doublet Higgs fields as follow,

$$\Phi = \begin{pmatrix} w^0 & x^- \\ y^+ & z^0 \end{pmatrix}, \quad \phi = \begin{pmatrix} n^+ \\ k^0 \end{pmatrix}, \tag{2}$$

which break the symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)$ down to $U(1)_{em}$. The bidoublet Higgs field Φ transforms as $\Phi(2,2,1)$ and doublet ϕ transforms as $\phi(1,2,1)$ under $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group. The numbers 2 and 1 in the Higgs fields refer to doublet and singlet respectively. The vacuum expectation values of the Higgs fields are choosen as follow,

$$\langle \Phi \rangle = \begin{pmatrix} 0 & 0 \\ 0 & z \end{pmatrix}, \quad \phi = \begin{pmatrix} 0 \\ k \end{pmatrix}, \tag{3}$$

which must satisfy the relation,

$$Q\langle \Phi \rangle = 0, \tag{4}$$

where

$$Q = T_{3L} + T_{3R} + I/2, \tag{5}$$

is the electromagnetic charge operator, such that the vacuum remains invariant under $U(1)_{em}$ gauge transformations, and *I* is the 'hypercharge-like' which can be addresed to a new kind of quantum numbers. For example, *I*=*B*-*L* in the left-right symmetry model based on *SO*(10) GUT.

The general potential which is consistent with renormalizability, gauge invariance, and discrete left-right symmetry, is given by,

$$\begin{aligned} V(\Phi,\phi) = & -\mu_1^2 Tr\left(\Phi^+\Phi\right) + \lambda_1 Tr\left(\Phi^+\Phi\right)^2 \\ & - \mu_2^2 Tr\left(\tilde{\Phi}^+\tilde{\Phi}\right) + \lambda_2 Tr\left(\tilde{\Phi}^+\tilde{\Phi}\right)^2 \\ & - \alpha^2\phi^+\phi + \lambda_3\left(\phi^+\phi\right)^2 \\ & + \lambda_4\phi^+\phi\left(Tr\left(\Phi^+\Phi\right) + Tr\left(\tilde{\Phi}^+\tilde{\Phi}\right)\right) \end{aligned} \tag{6}$$

where $\tilde{\Phi} = \tau_2\Phi\tau_2$, $\mu_i\,(i = 1, 2)$, α, and $\lambda_i\,(i = 1, 2, 3, 4)$ are parameters. After explicitly performing the calculations in order to find out the minimum value of $V(\Phi,\phi)$which is bounded from below and take the appropriate values of the parameters μ_i, α, and λ_i, we can have $z << k$.

The complete Lagrangian density *L* in our model is given by,

$$\begin{aligned} L = & -\tfrac{1}{4}\left(W_{\mu\nu L}W_L^{\mu\nu} + W_{\mu\nu R}W_R^{\mu\nu}\right) - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ & + \overline{\psi}_L\gamma^\mu D_{\mu L}\psi_L + \overline{\psi}_R\gamma^\mu D_{\mu R}\psi_R \\ & + Tr\left|\left(i\partial_\mu - \frac{g}{2}\tau W_{\mu L}\right)\Phi - \frac{g}{2}\Phi\tau W_{\mu R}\right. \\ & \left. - \frac{g'}{2}IB_\mu\Phi\right|^2 + \left|\left(i\partial_\mu - \frac{g}{2}\tau W_{\beta\mu R}\right)\phi\right|^2 \\ & - V(\Phi,\phi) - L_{mf}, \end{aligned} \tag{7}$$

where $D_{\mu L,R} = i\partial_\mu - \frac{g}{2}\tau W_{\mu L,R} - \frac{g'}{2}I$, *I* is the quantum number which is associated with *U*(1) generator in left-right symmetry model, γ^μ is the Dirac matrices, τ is the Pauli spin matrices, *g* is the *SU*(2) coupling (we have put $g_L = g_R = g$ due to the left-right symmetry model), *g'* is the *U*(1) coupling, and L_{mf} is the Lagrangian density mass terms for fermions.

3. The Gauge Bosons and Leptons Masses

3.1 The Gauge Bosons Masses

Due to the transformation properties of the Higgs fields, the relevant Lagrangian density mass terms for gauge bosons (L_B) in eq. (7) is given by,

$$\begin{aligned} L = & Tr\left|\left(-\frac{g}{2}\tau W_{\mu L}\right)\Phi - \frac{g}{2}\Phi\tau W_{\mu R}\right. \\ & \left. - \frac{g'}{2}IB_\mu\Phi\right|^2 + \left|\left(-\frac{g}{2}\tau W_{\beta\mu R}\right)\phi\right|^2. \end{aligned} \tag{8}$$

Substituting eq. (3) into eq. (8), the Lagrangian density of the gauge bosons mass terms read.

$$
\begin{aligned}
L_B = {} & \frac{g^2}{4}\left(z^2+k^2\right)\left(W^1_{\mu R}+iW^2_{\mu R}\right) \\
& \times\left(W^1_{\mu R}\text{-}iW^2_{\mu R}\right) \\
& +\frac{g^2z^2}{4}\left(W^1_{\mu L}+iW^2_{\mu L}\right)\left(W^1_{\mu L}\text{-}iW^2_{\mu L}\right) \\
& +\frac{z^2}{4}\left(gW^3_{\mu L}-g'B_\mu\right)^2 \\
& +\frac{g^2(z^2+k^2)}{4}\left(W^3_{\mu R}\right)^2 \\
& +\frac{gz^2}{2}\left(gW^3_{\mu L}-g'B_\mu\right)W^{\mu 3}_R.
\end{aligned}
\tag{9}
$$

To find out explicitly how eq. (9) look like, we define the new fields,

$$
\begin{aligned}
W^{\pm}_{\mu R} &= \frac{1}{\sqrt{2}}\left(W^1_{\mu R}\mp iW^2_{\mu R}\right), \\
W^{\pm}_{\mu L} &= \frac{1}{\sqrt{2}}\left(W^1_{\mu L}\mp iW^2_{\mu L}\right), \\
Z_{\mu L} &= \frac{gW^3_{\mu L}-g'B_\mu}{\sqrt{g^2+g'^2}}, \\
A_{\mu L} &= \frac{g'W^3_{\mu L}+gB_\mu}{\sqrt{g^2+g'^2}}, \\
W^3_{\mu R} &= X_{\mu R}.
\end{aligned}
\tag{10}
$$

Using the new fields in eq. (10), the form of eq. (9) reads,

$$
\begin{aligned}
L_B = {} & \frac{g^2}{4}\left(z^2+k^2\right)W^+_{\mu R}W^{\mu -}_R \\
& +\frac{g^2z^2}{4}W^+_{\mu L}W^{\mu -}_L+\frac{(g^2+g'^2)}{4}\left(Z_{\mu L}\right)^2 \\
& +\frac{g^2(z^2+k^2)}{4}\left(X_{\mu R}\right)^2 \\
& +\frac{g\sqrt{g^2+g'^2}\,z^2}{2}Z_{\mu L}X^{\mu}_R.
\end{aligned}
\tag{11}
$$

From eq. (11) we can see that there is no mixing in the $W^{\pm}_{\mu R}-W^{\pm}_{\mu L}$ basis. The charged gauge bosons masses in the new fields basis which defined in eq.(10) are given by,

$$
m_{W_R}=g\sqrt{\frac{z^2+k^2}{2}},\quad m_{W_L}=\frac{gz}{\sqrt{2}}, \tag{12}
$$

and for the neutral bosons sector we have a mixing term between $Z_{\mu L}$ and $X_{\mu R}$ fields. In the GWS model, we only have one type of charged gauge boson mass because we have only two boson fields W^+ and W^- with the same mass $m_{WL} = gv/2$.

The mass terms in the neutral bosons sector can be written in the matrix form, namely

$$
M^2 = \begin{matrix} \\ Z_{\mu L} \\ X_{\mu R} \end{matrix}
\begin{bmatrix} Z_{\mu L} & X_{\mu R} \\ \frac{(g^2+g'^2)z^2}{4} & \frac{gz\sqrt{g^2+g'^2}}{4} \\ \frac{gz\sqrt{g^2+g'^2}}{4} & \frac{g^2(z^2+k^2)}{4} \end{bmatrix} \tag{13}
$$

The eigenstates of the above matrix in $Z_{\mu 1}$ and $Z_{\mu 2}$ bosons can be written as follow,

$$
\begin{aligned}
Z_{\mu 1} &= Z_{\mu L}\cos\theta + X_{\mu R}\sin\theta, \\
Z_{\mu 2} &= -Z_{\mu L}\sin\theta + X_{\mu R}\cos\theta,
\end{aligned}
\tag{14}
$$

where the mixing angle θ satisfy the relation,

$$
\tan(2\theta)=\frac{2z^2\sqrt{1+\left(g'/g\right)^2}}{k^2\sqrt{1-\left(gz/gk\right)^2}}. \tag{15}
$$

The masses of the physical $Z_{\mu 1}$ and $Z_{\mu 2}$ bosons are given by,

$$
m_{Z_1}=\frac{1}{2}\left[A-B\right]^{1/2}, m_{Z_2}=\frac{1}{2}\left[A+B\right]^{1/2}, \tag{16}
$$

where

$$
\begin{aligned}
A &= \frac{(2g^2+g'^2)z^2+g^2k^2}{2}, \\
B &= \frac{\sqrt{(g^2k^2-g'^2z^2)+4g^2k^2(g^2+g'^2)}}{2},
\end{aligned}
$$

and the photon mass is zero (M_A= 0) as required.

3.2 Leptons masses

In our model, the leptons can acquire a mass via the ordinary Higgs mechanism if the non-zero quantum number I in the Lagrangian density mass terms are violated. In this scheme, the leptons acquire masses only from the expectation value of the bidoublet Higgs as follow,

$$
\begin{aligned}
L_{mf} &= G_l\bar{\psi}_L\langle\Phi\rangle\psi_R \\
&\quad + G^*_l\bar{\psi}_L\langle\tilde{\Phi}\rangle\psi_R + h.c.,
\end{aligned}
\tag{17}
$$

where G_l and G^*_l are the Yukawa couplings.

If we substitute the expectation value of the bidoublet Higgs in eq. (3) into eq. (17), then we have,

$$
L_{mf}=G_lz\bar{l}_Ll_R+G^*_lz\bar{\nu}_L\nu_R+h.c. \tag{18}
$$

If we use the requirement that the quantum number I must be zero in the Lagrangian density mass terms, then we can not use anymore eq. (17) or Higgs mechanism to generate the leptons masses.

4. Discussion

Using one bidoublet Higgs field Φ(2,2,1) which transforms as doublet under both $SU(2)_L$ and $SU(2)_R$ singlet under $U(1)$, and one additional doublet scalar Higgs Φ(1,2,1) which transforms as singlet under $SU(2)_L$, doublet under $SU(2)_R$ and singlet under $U(1)$ in the left-right symmetry model based on $SU(2)_L\otimes SU(2)_R\otimes U(1)$, we can obtain four massive gauge bosons with mass $m_{W_L}, m_{W_R}, m_{Z_1}, m_{Z_2}$, and one massless gauge boson which is known as photon. The charged gauge boson with mass m_{W_L} and the neutral gauge boson with mass m_{Z_1} can be associated with the known gauge bosons masses in GWS model.

To see explicitly the right charged current contribution to weak interaction at low energy, we should take the effective interaction in which the Lagrangian density is given by,

$$L_W = -\frac{4G_{FL}}{\sqrt{2}} J^{\mu L} J^{+}_{\mu L} - \frac{4G_{FR}}{\sqrt{2}} J^{\mu R} J^{+}_{\mu R}, \qquad (19)$$

where G_{FL} and G_{FR} are the Fermi couplings associated with left and the right charged currents $J_{\mu L}$ and $J_{\mu R}$ with the Fermi couplings are given by,

$$G_{FL} = \frac{\sqrt{2}g^2}{8m^2_{W_L}},\ G_{FR} = \frac{\sqrt{2}g^2}{8m^2_{W_R}}. \qquad (20)$$

Because $k >> z$, then it implies that $m_{W_L} << m_{W_R}$. When the value of $m_{W_L} << m_{W_R}$, as one can see from eq. (20), we then have $G_{FL} >> G_{FR}$. If the value of $G_{FL} >> G_{FR}$, then the structure of electroweak interaction for charged current which is known today dominant *V-A* interaction can be understood as the implication of the $m_{W_L} << m_{W_R}$. Our model also predict one new massive neutral bosons with mass m_{Z_2}. For the neutral bosons, we also have $m_{Z_1} << m_{Z_2}$ when $k << z$. Both the gauge bosons masses m_{W_L} and m_{Z_1} can be associated with the known gauge bosons masses in the GWS model. The existency of the new gauge bosons $W_{\mu R}$ and $Z_{\mu 2}$ with masses m_{W_R} and m_{Z_2} respectively can be tested in LHC machine.

In the GWS model which based on $SU(2)_L \otimes U(1)_Y$ gauge group with only one scalar Higgs $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ which transforms as doublet under $SU(2)_L$ and singlet under $U(1)_Y$ and its vacuum expectation value $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ we only have two massive physical boson fields,

$$W^{\pm}_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right), \quad Z_\mu = \frac{gW^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}}, \qquad (21)$$

with masses $m_W = gv/2$ and $m_z = \frac{v}{2}\sqrt{g^2 + g'^2}$ respectively, and one massless boson field

$$A_\mu = \frac{g' W^3_\mu + gB_\mu}{\sqrt{g^2 + g'^2}}. \qquad (22)$$

To see explicitly how large the masses of the m_{W_R} and m_{Z_2} are, we use the experimental data on muon polarization in $K_{\mu 2}$ decay, where P_μ = -1 for pure *V - A* interaction, gives[18)]

$$P_\mu = 0.967 \pm 0.047, \qquad (23)$$

which allows a four percent admixture of the *V – A* currents. From this fact and using eq. (20), we then obtain the value of the $m_{W_R} \approx 400$ GeV, and $m_{Z_2} \approx 451$ GeV.

From eq. (18), we can see that all leptons (including neutrinos) acquiring a mass via a Higgs mechanism if the non-zero quantum number *I* is allowed in Lagrangian density mass terms. The masses of the charged leptons are equal to the neutral leptons (neutrinos) if $G_l = G^*_l$. Recently, as dictated by the experimental data, the neutrino mass is very small compared to its generation pair charged lepton mass. In our model, a tiny neutrino mass can be obtained via a Higgs mechanism only if we put the Yukawa coupling $G_l >> G^*_l$ and the non-zero quantum number *I* is allowed in Lagrangian density mass terms. If we impose the requirement that the quantum number *I* must be zero in Lagrangian density mass terms, then we can not use the Higgs mechanism anymore to generate the fermions massess.

Another possibility for generating the fermions masses (charged and neutral leptons) in our model, without putting the Yukawa coupling $G_l >> G^*_l$, but allowed the non-zero value of hypercharge-like *I* in the Lagrangian density, is the Higgs mechanism followed by a seesaw-like mechanism. In this scheme, the neutrino masses read,

$$m_{\nu_l} = m^D_{\nu_l} m^{-1}_{Z_2} m^D_{\nu_l}, \qquad (24)$$

where m_{Z_2} is the massive neutral gauge boson mass in eq. (16) and $m^D_{\nu_l} = G^*_l z$. Meanwhile, the charged leptons masses read,

$$m_l = m^D_l m^{-1}_{Z_1} m^D_l, \qquad (25)$$

where $m^D_l = G_l\, z$ and m_{Z_1} is the neutral gauge boson mass in eq. (16).

In our model, we put the vacuum expectation value of doublet Higgs to be larger than the vacuum expectation value of the bidoublet Higgs in order to accommodate the maximally parity violation at low energy. This choice for the Higggs fields vacuum expectation values do not have any conflict to the present status of the Higgs particles because its existency have not been yet confirmed experimentally.

5. Conclusion

The structure of the electroweak interaction which is dominant *V-A* as known today can be undestood in a left-right symmetry model based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group by using one bidoublet and one doublet Higgs fields. The contribution of right charged current interaction to weak interaction is very small due to the very large of m_{W_R} compared to m_{W_L} . Leptons can obtain a mass via two mechanisms, first via a Higgs mechanism with a non-zero 'hypercharge-like' *I* allowed in Lagrangian density mass terms and the Yukawa couplings $G_l >> G_l^*$, and the second via a Higgs mechanism followed by a seesaw-like mechanism without the requirement that the Yukawa couplings $G_l >> G_l^*$.

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