Symmetry Breaking and Mass Generation of the Exotic Scalar Bosons in a Left-Right Symmetric Model with gauge symmetry $SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \otimes \mathcal{P}$

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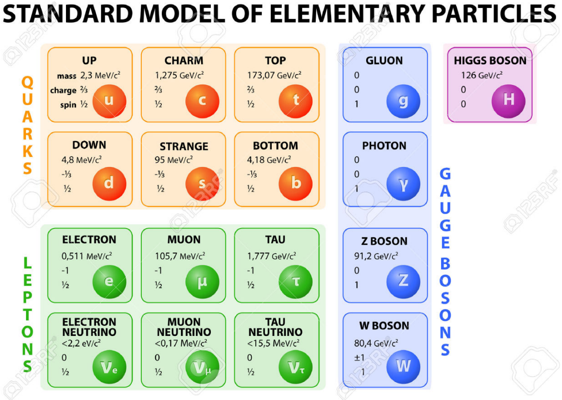
Outline:

- Introduction.
- Proposal of the Leptonic Sector.
- Proposal of the Scalar Sector
- Mass Matrices of the Exotic Scalar Bosons
- Identifying the SM's Higgs Boson
- Conclusions

Standard Model (SM) of Particle Physics



The SM of particle physics is surely one of the most successful theories in physics. However, there are certain questions that cannot be explained.

Open Questions of the Standard Model

- Neutrino oscillation which demands that neutrinos in fact do have a non-vanishing mass,
- The massive neutrinos will be Dirac or Majorana.
- The hierarchy problem.
- The radiation and matter made of SM particles only account for about 5 % of the mass and energy content in the universe. Roughly 27 % are attributed to non-luminous dark matter and the remaining roughly 68 % are so-called dark energy.
- The parity violation on weak interactions.
- The origin of the matter-antimatter asymmetry.
- why there are three generations of fundamental fermions.

The Model: $SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \otimes \mathcal{P}$

The Leptonic Sector:[3]

$$L_\ell = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L ; \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \sim (\mathbf{2}_L, \mathbf{1}_R, -1) \tag{1}$$

$$R_\ell = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_R ; \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_R ; \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_R \sim (\mathbf{1}_L, \mathbf{2}_R, -1) \tag{2}$$

Where: $\ell = e, \mu, \tau$.

Gell Mann - Nishijima relation (Electroweak sector):

$$Q = T_{3L} + T_{3R} + \frac{1}{2}(B - L) \tag{3}$$

[3] G. Senjanovic, Spontaneous Breakdown of Parity in a Class of Gauge Theories, Nucl. Phys. B 153, 334 (1979)

The Model: $SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \otimes \mathcal{P}$

The Leptonic lagrangean Density:

$$\mathcal{L}^{lep}(x) = i \left\{ \bar{L}_l(x)\gamma^{\mu} D^L_{\mu} L_l(x) + \bar{R}_l(x)\gamma^{\mu} D^R_{\mu} R_l(x) \right\} + H.C. \quad (4)$$

Where the covariant derivatives of this sector take the form:

$$\begin{aligned} D^L_{\mu} &\equiv \partial_{\mu} + \frac{ig}{2}\,\bar{\tau}.\bar{W}^L_{\mu} - \frac{ig'}{2}\,B_{\mu} \\ D^R_{\mu} &\equiv \partial_{\mu} + \frac{ig}{2}\,\bar{\tau}.\bar{W}^R_{\mu} - \frac{ig'}{2}\,B_{\mu} \end{aligned} \quad (5)$$

the (4) eq. remains unchanged by imposing a generalized partity $\mathcal{P}$, under which:

$$g_L \leftrightarrow g_R,\; W_{L\mu} \leftrightarrow W^{\mu}_R,\; f_L \leftrightarrow f_R,\; \chi_L \leftrightarrow \chi_R, \Phi_i \leftrightarrow \Phi^{\dagger}_i, \tilde{\Phi}_i \leftrightarrow \tilde{\Phi}^{\dagger}_i,$$

where $\tilde{\Phi}_i = \tau_2 \Phi^*_i \tau_2$. However, the invariance under $\mathcal{P}$ implies equality of gauge couplings $g_L = g_R \equiv g$ at the energy at which these symmetries are realized.

The Model: $SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \otimes \mathcal{P}$

The Scalar Sector: The scalar sector consists of two bi-doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \; \Phi_2 = \begin{pmatrix} \eta_1^0 & \eta_2^+ \\ \eta_1^- & \eta_2^0 \end{pmatrix}, \qquad (6)$$

to generate neutrino, leptons and quark masses; and two doublets $\chi_L \sim (2,1,1)$ and $\chi_R \sim (1,2,1)$ to break the gauge symmetry down to $U(1)_Q$.

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \qquad (7)$$

The χ_R doublet protects the left-right symmetry of the model.

The Scalar Sector

The covariant derivatives:

$$D_\mu \Phi = \partial_\mu \Phi - \frac{ig}{2} \bar{W}^L_\mu . \bar{\tau}\, \Phi + \frac{ig}{2}\, \Phi\, \bar{W}^R_\mu . \bar{\tau}$$

$$D_\mu \chi_L = \partial_\mu \chi_L - \frac{i}{2} g \bar{\tau} \cdot \bar{W}^L_\mu - \frac{i}{2} g' B_\mu \chi_L \qquad (8)$$

$$D_\mu \chi_R = \partial_\mu \chi_R - \frac{i}{2} g \bar{\tau} \cdot \bar{W}^R_\mu - \frac{i}{2} g' B_\mu \chi_R$$

The Higgs potential:

$$V = V^{(2)} + V^{(4a)} + V^{(4b)} + V^{(4c)} + V^{(4d)} + V^{(4e)}, \qquad (9)$$

which respects the symmetries of the model.

The Scalar Sector

$$V^{(2)} = \frac{1}{2}\sum_{i=1,2}^{2}\left[\mu_{ii}^2\, Tr(\Phi_i^\dagger\Phi_i) + H.c.\right] + \mu_{LR}^2\left(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R\right)$$

$$V^{(4a)} = \frac{1}{2}\sum_{i=1,2}^{2}\left[\lambda_{ii}\, Tr(\Phi_i^\dagger\Phi_i)^2 + H.c.\right],$$

$$V^{(4b)} = \frac{1}{2}\sum_{i=1,2}^{2}\lambda'_{ii}\left(Tr\Phi_i^\dagger\Phi_i\right)^2, \; V^{(4c)} = \rho_{12}\, Tr\left(\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2\right),$$

$$V^{(4d)} = \frac{1}{2}\left[\sum_{i=1,2}^{2}(\Lambda_{ii}\, Tr\Phi_i^\dagger\Phi_i(\chi_L^\dagger\chi_L\chi_R^\dagger\chi_R) + \overline{\Lambda}_{ii}(\chi_L^\dagger\Phi_i\Phi_i^\dagger\chi_L + \chi_R^\dagger\Phi_i\Phi_i^\dagger\chi_R) + \right.$$

$$\left. + \; \overline{\Lambda}'_{ii}(\chi_L^\dagger\tilde{\Phi}_i\tilde{\Phi}_i^\dagger\chi_L + \chi_R^\dagger\tilde{\Phi}_i\tilde{\Phi}_i^\dagger\chi_R))\right]$$

$$V^{(4e)} = \lambda_{LR}\left[(\chi_L^\dagger\chi_L)^2 + (\chi_R^\dagger\chi_R)^2\right].$$

The Scalar sector

The Lagrangean density of the scalar sector is given by:

$$\begin{aligned}\mathcal{L}^H &= Tr[(D_\mu\Phi)^\dagger D^\mu\Phi)] + (D_\mu\chi_L)^\dagger D^\mu\chi_L + \\ &+ (D_\mu\chi_R)^\dagger D^\mu\chi_R] + V,\end{aligned}$$

The scalar potential given in (9) is a simpler expression compared with the scalar one written in a previous work[4], where we have used additional discrete symmetries, like Z_5 and $Z_2 \times Z_2$ over the scalar fields to reduce and to forbid several terms of the potential.

[4] Henry Diaz, V. Pleitez, O. Pereyra Ravinez, Dirac neutrinos in a $SU(2)$ left-right symmetric model

The Fields Transformation

In this LR model, the fields follow the transformation rules given by:

$$
\begin{aligned}
L' &= U_L\, L; \quad \text{where} \quad U_L = e^{i\vec{\tau}\cdot\vec{\alpha}}, \\
R' &= U_R\, R; \quad \text{where} \quad U_R = e^{i\vec{\tau}\cdot\vec{\beta}}, \\
\Phi'_i &= U_L \Phi_i U_R^{\dagger}, \\
\chi'_L &= U_L\, \chi_L, \\
\chi'_R &= U_R\, \chi_R, \\
W'_{\mu L,R} &= U_{L,R} W_\mu U_{L,R}^{\dagger} + (\partial_\mu U_{L,R}) U_{L,R}^{\dagger}
\end{aligned}
$$

These fields are invariant under the gauge group: $SU(2)_L \otimes SU(2)_R$

The Mass Generation

The vacuum expectation values (*VEVs*) are:

$$< \Phi_1 >= \frac{1}{\sqrt{2}} \left(\begin{array}{cc} k_1 & 0 \\ 0 & k_1' \end{array} \right), \quad < \Phi_2 >= \frac{1}{\sqrt{2}} \left(\begin{array}{cc} k_2 & 0 \\ 0 & k_2' \end{array} \right), \tag{10}$$

and

$$\langle \chi_L \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_L \end{array} \right), \quad \langle \chi_R \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_R \end{array} \right), \tag{11}$$

In general, we will write the neutral components of the scalars as

$$\langle x_i \rangle = \frac{1}{\sqrt{2}} (v_i + R_i + iI_i) e^{i\theta_i} \tag{12}$$

where v_i, θ_i are real numbers and R_i, I_i Hermitian fields. However, here we will consider all VEVs real, i.e., $\theta_i = 0$ for all i running over the bi-doublets and doublets.

The constraint equations

The constrain equations are obtained when the potential is expanded around of its minimun value (regarding the lineal fields's coefficients). Three of the six equations are shown below:

$$
\begin{aligned}
(a) \qquad & k_1\mu_{11}^2 + (\lambda_{11}+\lambda'_{11})k_1^3 + \lambda'_{11}k_1k_1'^2 \\
+ \quad & \frac{k_1}{2}(v_L^2+v_R^2)(\Lambda_{11}+\overline{\Lambda}'_{11}) + \frac{1}{2}k_1k_2^2\rho_{12} = 0,
\end{aligned}
$$

$$
\begin{aligned}
(b) \qquad & k_1'\mu_{11}^2 + (\lambda_{11}+\lambda'_{11})k_1'^3 + \lambda'_{11}k_1'k_1^2 \\
+ \quad & \frac{k_1'}{2}(v_L^2+v_R^2)(\Lambda_{11}+\overline{\Lambda}_{11}) + \frac{1}{2}k_1'k_2'^2\rho_{12} = 0,
\end{aligned}
$$

$$
\begin{aligned}
(c) \qquad & k_2\mu_{22}^2 + (\lambda_{22}+\lambda'_{22})k_2^3 + \lambda'_{22}k_2k_2'^2 \\
+ \quad & \frac{k_2}{2}(v_L^2+v_R^2)(\Lambda_{22}+\overline{\Lambda}'_{22}) + \frac{1}{2}k_2k_1^2\rho_{12} = 0,
\end{aligned}
$$

Mass Matrices of the Exotic Scalar Bosons

Expanding the neutral scalar fields around theirs VEVs:

For the bi-doublets:

$$\Phi_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(k_1 + H_{1a} + i\, I_{1a}) & \eta_1^+ \\ \phi_1^- & \frac{1}{\sqrt{2}}(k_1' + H_{2a} + i\, I_{2a}) \end{pmatrix},$$

$$\Phi_2 = \begin{pmatrix} \frac{1}{\sqrt{2}}(k_2 + H_{1b} + i\, I_{1b}) & \eta_2^+ \\ \phi_2^- & \frac{1}{\sqrt{2}}(k_2' + H_{2b} + i\, I_{2b}) \end{pmatrix},$$

For the doublets:

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \frac{1}{\sqrt{2}}(v_L + H_{1L} + i\, I_{1L}) \end{pmatrix}, \quad \chi_R = \begin{pmatrix} \chi_R^+ \\ \frac{1}{\sqrt{2}}(v_R + H_{1R} + i\, I_{1R}) \end{pmatrix},$$

Charged Simply Scalars Fields

After using the constraint equations and diagonalizing the mass matrix, it is obtained:

$$
\begin{aligned}
m_{H_1^+} &= v_R\sqrt{-\frac{1}{2}(\Lambda_{11}+\overline{\Lambda}'_{11})}, \\
m_{H_2^-} &= v_R\sqrt{-\frac{1}{2}(\Lambda_{11}+\overline{\Lambda}_{11})}, \\
m_{H_3^+} &= \sqrt{k_2^2\,\lambda_{22}-\frac{v_R^2}{2}(\Lambda_{22}+\overline{\Lambda}'_{22})}, \\
m_{H_4^-} &= \sqrt{k_2^2\,\lambda_{22}-\frac{v_R^2}{2}(\Lambda_{22}+\overline{\Lambda}_{22})}, \\
m_{H_5^+} &= m_{H_6^+} = k_2\sqrt{-(2\Lambda_{22}+\overline{\Lambda}_{22}+\overline{\Lambda}'_{22})}
\end{aligned}
\tag{13}
$$

Charged Simply Scalars Fields

From the previously calculated mass values, we have:

$$\begin{aligned} \Lambda_{11} + \overline{\Lambda}'_{11} &< 0, \qquad \Lambda_{11} + \overline{\Lambda}_{11} < 0, \\ \Lambda_{22} + \overline{\Lambda}'_{22} &< 0, \qquad \Lambda_{22} + \overline{\Lambda}_{22} < 0, \\ 2\Lambda_{22} + \overline{\Lambda}_{22} + \overline{\Lambda}'_{22} &< 0, \end{aligned} \tag{14}$$

Remmember that: $V_R \gg X$, where X represents another VEVs different from V_R.

$$m_{H_3^+} \approx v_R \sqrt{\frac{-(\Lambda_{22} + \overline{\Lambda}'_{22})}{2}} - \frac{k_2^2\,\lambda_{22}}{v_R \sqrt{-2(\Lambda_{22} + \overline{\Lambda}'_{22})}} + \mathcal{O}(1/v_R^3).$$

$$m_{H_4^+} \approx v_R \sqrt{\frac{-(\Lambda_{22} + \overline{\Lambda}_{22})}{2}} - \frac{k_2^2\,\lambda_{22}}{v_R \sqrt{-2(\Lambda_{22} + \overline{\Lambda}_{22})}} + \mathcal{O}(1/v_R^3).$$

Neutral Scalars Fields

1. The Non-massive neutral fields (three Goldstone Bosons):

$$m_{H_1}^2 = m_{H_2}^2 = m_{H_3}^2 = 0, \quad (15)$$

2. The Massive neutral fields:

$$\begin{aligned} m_{H_4}^2 &= \frac{1}{2}\left[k_2^2(\lambda_{22}+2\lambda'_{22}) + \lambda_{LR}v_R^2 - \sqrt{\Delta}\right], \\ m_{H_5}^2 &= k_2^2\,\lambda_{22}, \\ m_{H_6}^2 &= \frac{1}{2}\left[k_2^2(\lambda_{22}+2\lambda'_{22}) + \lambda_{LR}v_R^2 + \sqrt{\Delta}\right], \end{aligned} \quad (16)$$

where:

$$\begin{aligned} \Delta &= \left[\lambda_{LR}v_R^2 - k_2^2(\lambda_{22}+2\lambda'_{22})\right]^2 \\ &+ 2k_2^2\,v_R^2\left(\overline{\Lambda}_{22}+\overline{\Lambda}'_{22}\right)^2, \end{aligned} \quad (17)$$

Neutral Scalars Fields

If the existence of three massive neutral Higgs is observed, it can be said that one of these fields would correspond to the Higgs boson of the SM. Furthermore, from the mass expressions (16), it is observed that the parameter λ_{22} must be positive, as was noticed on the previous section, such that it verifies the following:

$$m_{H_6}^2 \gg m_{H_4}^2, m_{H_5}^2,$$

for values $v_R \gg X$, where X represents any other VEV different from v_R.
In the same way, for the another neutral scalar fields (which comes from the imaginary part)

$$m_{I_1}^2 = m_{I_2}^2 = m_{I_3}^2 = m_{I_4}^2 = m_{I_5}^2 = m_{I_6}^2 = 0.$$

we get six additonal Goldstone Bosons.

Fenomenology: Identifying the Higgs boson

Regarding the neutral scalar field, see Eq. (16), and the condition $V_R \gg X$, it is obtained: ,

$$
\begin{aligned}
m_{H_4} &\approx k_2 \sqrt{\lambda_{22} + \lambda'_{22} + \lambda'^2_{22} - \frac{(\overline{\Lambda}'_{22} + \Lambda_{22})^2}{2\lambda_{LR}}} \\
&+ \mathcal{O}(1/v_R^2) \\
m_{H_5} &= k_2 \sqrt{\lambda_{22}}, \\
m_{H_6} &\approx v_R \sqrt{\lambda_{LR}} + \mathcal{O}(1/v_R),
\end{aligned} \tag{18}
$$

Making a little phenomenological analysis of the results mentioned above, we have:

Fenomenology: Identifying the Higgs boson

- If $m_{H_6} > m_{H_4} > m_{H_5}$, then m_{H_5} will be MS Higgs Boson. According to the particle data group[5]:
  $M_{Higgs} = 125.10 \pm 0.14$ GeV. Thus:

$$M_{Higgs} = 125.10 = M_{H_5} = k_2 \sqrt{\lambda_{22}}, \tag{19}$$

From the SM, k_2 can take the value 246 GeV . From this result, it is verified:

$$\lambda_{22} \geq 0.259 \quad . \tag{20}$$

- If $m_{H_6} > m_{H_5} > m_{H_4}$
  Therefore, m_{H_4} will be the MS Higgs Boson,

[5] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019

Fenomenology: Identifying the Higgs boson

$$k_2\sqrt{\lambda_{22}+\lambda'_{22}+\lambda'^2_{22}-\frac{(\overline{\Lambda}'_{22}+\Lambda_{22})^2}{2\lambda_{LR}}}=125.10 \qquad (21)$$

As already mentioned, at SM energies scales, the maximum value that k_2 can take the value 246 GeV, obtaining:

$$\lambda_{22}+\lambda'_{22}+\lambda'^2_{22}-\frac{(\overline{\Lambda}'_{22}+\Lambda_{22})^2}{2\lambda_{LR}}\geq 0.067. \qquad (22)$$

It is known, according to the bibliographies[6], that first, the symmetry is broken through the heaviest VEV, V_R, whose minimun value is the order of 1 TeV (in general $V_R > 1$ TeV).

[6] Chang Hun Lee, Doctor of Philosophy, 2017, Left-Right Symmetric Model and its TeV-Scale Phenomenology, Dissertation directed by: Rabindra N. Mohapatra.

Fenomenology: Identifying the Higgs boson

The most massive Higgs boson is m_{H_6}, as a result of its direct dependence on V_R, which is the largest VEV (in TeV), compared to the others ones, which are solutions of the bonded equations. For example, if $_{LR} = 16$ and $V_R = 1$ TeV, we obtained: $m_{H_6} = 4$ TeV.

Conclusions

- According to the results obtained, the model presents: 3 massive neutral Higgs bosons, nine neutral ones non-massive and six charged simply massive particles.
- Although I didn't mention here, the model proposes six massive vector bosons (Z_0, Z_0', $W_L^{\pm}$, $W_R^{\pm}$) and a non-massive one, which is the photon, A_μ.
- The nine non-massive bosons correspond to nine goldstone bosons, these are absorbed to give masses to the massive vector bosons and the three higgs bosons (H_4, H_5 and H_6) proposed by the model.
- The restrictions obtained in the model parameters will serve for future phenomenological calculations, and can be compared with those obtained in future experiments that may be developed.