Spontaneous parity breaking and fermion masses

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- Parity breaking dawn

"If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sence there will still be overall right-left symmetry".

Lee-Yang 1956

- Gauge group

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

$$SU(2)_L \xleftrightarrow{\mathrm{P}} SU(2)_R$$

with:

$$Q = T_3 + T_3^* + Y/2$$

- Fermion representation

$$\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \ \nu_R, \ e_R \quad \xleftrightarrow{\mathrm{P}} \quad \mathrm{L_R} = \begin{pmatrix} \mathrm{N} \\ \mathrm{E} \end{pmatrix}_{\mathrm{R}}, \ \mathrm{N_L}, \ \mathrm{E_L}$$

$$(\frac{1}{2}, 0, -1); (0, 0, 0); (0, 0, -2) \quad (0, \frac{1}{2}, -1); (0, 0, 0); (0, 0, -2)$$

- **Higgs sector**

- Doublets

$$\chi_L(v_L) \quad \xleftrightarrow{P} \quad \chi_R(v_R)$$

$$(\frac{1}{2}, 0, 1) \qquad (0, \frac{1}{2}, 1)$$

- Mixed

$$\Phi \longleftrightarrow (1/2, 1/2, 0) \longleftrightarrow k, k'$$

- Neutral Singlets

$$S \longleftrightarrow (0, 0, 0) \longleftrightarrow s$$

- **Symmetry breaking hierarchy**

$$s_{GUT} >> v_R >> v_L >> k, k'$$

- **Basic requirements:**
  1. **Consistent gauge boson masses. Standard model.**
  2. **Small neutrino mass. See-saw.**
  3. **Small electron mass.**

- **Gauge bosons**

  - Charged vector bosons

$$\mathrm{M^2_{W_L}} \simeq \frac{1}{4}\mathrm{g_L^2 v_L^2} \qquad \mathrm{M^2_{W_R}} \simeq \frac{1}{4}\mathrm{g_R^2 v_R^2}$$

  - General angles

$$(g_L,\, g_R,\, g') \longleftrightarrow (g_L,\, \sin\theta_W,\, \sin\beta)$$

$$sin^2\theta_W \equiv \frac{g_R^2 g'^2}{g_R^2 g_L^2 + g_R^2 g'^2 + g_L^2 g'^2} \qquad sin^2\beta \equiv \frac{g'^2}{g_R^2 + g'^2}$$

$$\omega = v_L/v_R,\ \omega^2 \ll 1$$

- **Neutral vector bosons**

$$\begin{aligned} M_\gamma &\equiv 0 \\ M_Z^2 &\equiv \frac{1}{4}\frac{v_L^2 g_L^2}{\cos^2\theta_W}\{1-\omega^2\sin^4\beta\} \\ M_{Z'}^2 &\equiv \frac{1}{4} v_R^2 g_L^2 \tan^2\theta_W \tan^2\beta\{1+\frac{\omega^2 sin^2 2\beta}{4\sin^2\theta_W}\} \end{aligned}$$

- **The unification condition and ρ parameter**

$$\mathrm{e} = \mathrm{g_L}\sin\theta_\mathrm{W}, \qquad \rho = \frac{\mathrm{M_{WL}^2}}{\mathrm{M_Z^2}\cos^2\theta_\mathrm{W}}\{1-\omega^2\sin^4\beta\}$$

- **Parameters:** g_L, g_R, g', v_L, v_R $(g_L = g_R)$

$$Inputs = \begin{cases} M_W = 80.4 GeV \\ \sin^2\theta_W = 0.2230 \\ \alpha(M_Z) = 1/128 \end{cases} \qquad Outputs = \begin{cases} v_L = 248 GeV \\ g_L = 0.6635 \\ \sin^2\beta = 0.286 \end{cases}$$

- **Only one unknown** $\longrightarrow v_R$

- Neutral currents couplings to Z and Z'

$$J_\mu = \frac{g_L}{\cos\theta_W}\gamma_\mu \quad \{ \quad (1-\omega^2\sin^4\beta)T_3 - \omega^2\sin^2\beta\cos^2\beta T_3^* \\ - \quad Q\sin^2\theta_W(1-\frac{\omega^2\sin^4\beta}{\sin^2\theta_W})\}$$

$$J'_\mu = g_L\tan\theta_W\tan\beta\gamma_\mu \quad \{ \quad (1+\frac{\omega^2\sin^2\beta\cos^2\beta}{\sin^2\theta_W})T_3 + \frac{1}{\sin^2\beta}T_3^* \\ - \quad Q(1+\omega^2\cos^2\beta\sin^2\beta)\}$$

- High precision LEP and SLC data

$$\begin{aligned} g_V^{L,R} &= g_V^{SM} - (\omega^2\sin^4\beta)\{T_3^L - 2Q\} \\ g_A^{L,R} &= g_A^{SM} - (\omega^2\sin^4\beta)\{T_3^L\} \end{aligned}$$

- Data

$$\begin{cases} g^{\nu e}_{exp} = 0.528 \pm 0.085 \\ \Gamma^{inv}_{exp}(Z) = 498.8 \pm 1.5 MeV \\ g^{\nu\mu}_{exp} = 0.502 \pm 0.017 \end{cases}$$

- SM

$$\begin{cases} g_{SM} = 0.5042 \\ \Gamma^{inv}_{SM}(Z) = 501.65 \pm 0.15 MeV \end{cases}$$

- Bounds at 95%

$$(\omega^2\sin^4\beta) < 10^{-4} \qquad v_R > 30\, v_L \qquad M_{Z'} > 800 \quad GeV$$

- **Fermion masses**

  - **General Yukawa lagrangian**

$$
\begin{aligned}
\mathcal{L} &= f\{\overline{\ell_L}\chi_L\nu_R + \overline{L_R}\chi_R N_L + \overline{e_R}\tilde{\chi}_L\ell_L + \overline{E_L}\tilde{\chi}_R L_R\} \\
&+ f'\{\overline{\ell_L}\chi_L N_L^C + \overline{L_R}\chi_R\nu_R^C\} \\
&+ gS_M\{\overline{N_L^C}N_L + \overline{\nu_R^C}\nu_R\} + g'S_D\{\overline{\nu_R}N_L\} + g^* S_D\{\overline{e_R}E_L\} \\
&+ f"\{\overline{\ell_L}\Phi L_R\} + h.c.
\end{aligned}
$$

  - **Neutral fermions**

$$
\begin{aligned}
\mathcal{L} &= f v_L\overline{\nu_L}\nu_R + f' v_L\overline{\nu_L^c}N_L + f v_R\overline{N_R}N_L + f' v_R\overline{N_R^C}\nu_R \\
&+ g s_M\overline{N_L^C}N_L + g s_M\overline{\nu_R^C}\nu_R + g' s_D\overline{\nu_R}N_L \\
&+ g" k\overline{\nu_L}N_R,
\end{aligned}
$$

  - **Charged fermions**

$$
\mathcal{L} = f v_L\overline{e_L}e_R + f v_R\overline{E_R}E_L + g' s_D\overline{e_R}E_L + g" k\overline{e_L}E_R,
$$

Change Dirac 4-spinor basis to Majorana 2-spinor basis

$$\chi_i = \psi_{iL} + \psi_{iL}^C \qquad \omega_j = \psi_{jR} + \psi_{jR}^C, \qquad i,j = \nu, N$$

Basis: $(\chi_\nu;\, \omega_N;\, \chi_N;\, \omega_\nu)$

Neutrino mass matrix

$$M_{\nu,N} = \begin{pmatrix} 0 & \frac{k}{2} & v_L & \frac{v_L}{2} \\ \frac{k}{2} & 0 & \frac{v_R}{2} & v_R \\ v_L & \frac{v_R}{2} & s_M & \frac{s_D}{2} \\ \frac{v_L}{2} & v_R & \frac{s_D}{2} & s_M \end{pmatrix}$$

Charged fermion mass matrix

$$M_{e,E} = \begin{pmatrix} 0 & k' & 0 & v_L \\ k' & 0 & v_R & 0 \\ 0 & v_R & 0 & s_D \\ v_L & 0 & s_D & 0 \end{pmatrix}$$

For this last case, we recover the Dirac formalism by the standard $\pi/4$ rotations over the Majorana fields.

Model I

$$s_D \simeq s_M \simeq s_{GUT} = 10^{16} GeV,$$

$$\begin{cases} m_{\nu 1} = v_L^2/s_{GUT} \\ m_{\nu 2} = v_R^2/s_{GUT} \\ m_{N1} \simeq m_{N2} \simeq s_{GUT} \end{cases} \qquad \begin{cases} m_e = v_L v_R/s_{GUT} \\ m_E = s_{GUT} \end{cases}$$

$v_L = v_{Fermi}$, $s_{GUT} = 10^{16}$ GeV ($v_R = 10^{10}$ GeV)

Consequences

$$\bullet \begin{cases} m_{\nu 1} \simeq 10^{-2}\, eV \\ m_{\nu 2} \simeq 10\, TeV \\ m_{N1} \simeq m_{N2} \simeq 10^{16}\, GeV \\ m_e \simeq 1\, MeV \\ M_E \simeq 10^{16}\, GeV \end{cases}$$

- No new gauge bosons with $v_R = 10^{10}$.
- New heavy neutrinos with masses in the TeV region.
- v_R is of the order of the Peccei-Quinn symmetry breaking scale. Small value for the θ-angle of the strong CP problem.

Model II

$$s_M \simeq s_{GUT}, s_D << s_M$$

$$\begin{cases} m_{\nu 1} = v_L^2/s_{GUT} \\ m_{\nu 2} = v_R^2/s_{GUT} \\ m_{N_1,N_2} = s_{GUT} \pm s_D/2 \end{cases} \qquad \begin{cases} m_e = v_L v_R/s_D \\ m_E = s_D \end{cases}$$

$v_L = v_{Fermi} \longrightarrow v_R \simeq 10^4$ GeV and $s_D \simeq 10^{10}$ GeV.

Consequences

- Experimentally accessible new neutral current.
- $m_{\nu 1} = 10^{-2} - 10^{-3}$ eV; $m_{\nu 2} = 1 - 0.1$ eV.
  Orthogonal.
- The Peccei-Quinn symmetry breaking scale.

Other Families

- Different Dirac singlets. One Majorana singlet. Degenerate neutrino mass spectrum.

- Small mixing angles $\theta_{mix} \simeq m_\nu/m_N$.

- Increase the number of right-handed neutrinos. Fine-tuning in the neutrino mass matrix. Singular neutrino mass matrix.

- Mixing angles and neutrino masses is an open question. LEP and SLC gives the boundsin $\theta^2_{mix} < 10^{-2} - 10^{-3}$.

- Singlet proliferation. Neutrino hierarchy.

Conclusions

♣ Spontaneously broken parity models with a consistent fermion mass spectrum can be built at intermediate scales from 10^3 to 10^{10} GeV.

♣ The electron mass can be generated by a "see-saw" mass relation, analogous to the neutrino sector.

♣ Various scenarios for neutrino masses are possible and a more clear experimental definition on neutrino masses will allow to test their reality.

♣ Neutral heavy gauge bosons Z and Z', coupled to ordinary and new mirror fermions. This is a departure from other models that propose gravitation as the connection between the left and right sectors.

♣ Experimental consequences of the model could be found at the next generation of colliders.

♣ CP and $N = 3$?

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