CP-mirror Extension of Standard Model in $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_I$

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DESY-Theory Workshop 27 - 30 September 2011
Cosmology Meets Particle Physics: Ideas and Measurement

INTRODUCTION

- Many Reasons, why the Standard Model (SM) has to be extended.
- Eventhough it has passed many precission test, but it doesn't explain many phenomena.
- Among others is the smallness of neutrino masses.
- Among many extension of the SM, are the concept of mirror fermion.
  (Maybe the oldest reference: [J.C. Pati and A. Salam, Phys. Lett. **B58** (1975) 333])
- And also the ideas about the parity symmetry in Left-Right Model
  [J. C. Pati and A. Salam, Phys. Rev. **D 10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. **D 11**, 566 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. **D 12**, 1502 (1975); R. N. Mohapatra and R. E. Marshak, Phys. Lett. B **91**, 222 (1980).]

Mirror Model under SU(3)⊗SU(2)$_L$⊗SU(2)$_R$⊗U(1)$_I$.

- The original LR-model usually have both left and right handed doublet fermions.
- But some recent models, just doubled the SM particles (with L ↔ R) → Mirror (SM) fermion.
  [Among others: Y. A. Coutinho, J. A. Martins Simoes, C. M. Porto, Eur. Phys. J.**C18**, 779 (2001); J. A. Martins Simoes, J. Ponciano, Eur. Phys. J.**C30**, 007 (2003); de Almeida, F. M. L., Jr.; Coutinho, Y. A.; Simoes, J. A. Martins; Ramalho, A. J.; Pinto, L. Ribeiro; Wulck, S.; Do Vale, M. A. B, Phys. Rev. D 81, 053005 (2010)] . All fermion masses is through Dirac seesaw mechanism, except the neutrino which is through double seesaw.
- Other type of mirror: Doubling the SM particles and the gauge group [R. Foot, Phys. Rev. D **78**, 043529 (2008); P. Ciarcellutia and R. Foot, Phys. Lett. B **679** 3, 278-281; R. Foot and R. Volkas, Phys. Lett. B **645**, 1, 75-81].

CP-Mirror Model

- Proposing a model under SU(3)⊗SU(2)$_L$⊗SU(2)$_R$⊗U(1)$_I$ gauge, with the weak gauge coupling $g_L = g_R = g$, the U(1)$_I$ coupling g', and the EM. charge is $Q = T_{3L} + T_{3R} + \frac{I}{2}$.
- Doubled the SM particles (SM + right handed neutrino singlet).
- With parity mirror $L \leftrightarrow R$, and Charge conjugation.
- The mirror particles will have: $I \to -I$; the SU(2) T_3 quantum number $T_{3L} \to -T_{3R}$ (As consequence $Q \to -Q$), the singlet $R \to L$, and the color quantum number $r, b, g \to \bar{r}, \bar{b}, \bar{g}$.
- The particle and its mirror has the same fermion number.
- The model is assumed to be symmetric under $L \leftrightarrow R$ and C (CP - mirroring).
- Motivation: Neutrino masses, Beauty, (and Speculation)

Particle and CP-mirror particle contents

$$l_L = \begin{pmatrix} \nu_2^0 \\ e^- \end{pmatrix}_L (\mathbf{1},\mathbf{2},\mathbf{1},\text{-}1); \quad \nu_{1R}^0\ (\mathbf{1},\mathbf{1},\mathbf{1},0); \quad e_R^-\ (\mathbf{1},\mathbf{1},\mathbf{1},\text{-}2)$$

$$L_R = \begin{pmatrix} E^+ \\ \nu_2^0 \end{pmatrix}_R (\mathbf{1},\mathbf{1},\mathbf{2^*},1); \quad \nu_{1L}^0\ (\mathbf{1},\mathbf{1},\mathbf{1},0); \quad E_L^+\ (\mathbf{1},\mathbf{1},\mathbf{1},2)$$

$$q_L = \begin{pmatrix} u^{2/3} \\ d^{-1/3} \end{pmatrix} (\mathbf{3},\mathbf{2},\mathbf{1},1/3); \quad u_R^{2/3}\ (\mathbf{3},\mathbf{1},\mathbf{1},4/3); \quad d_R^{-1/3}\ (\mathbf{3},\mathbf{1},\mathbf{1},\text{-}2/3)$$

$$Q_R = \begin{pmatrix} D^{1/3} \\ U^{-2/3} \end{pmatrix} (\mathbf{3^*},\mathbf{1},\mathbf{2^*},\text{-}1/3); \quad U_L^{-2/3}\ (\mathbf{3^*},\mathbf{1},\mathbf{1},\text{-}4/3); \quad D_L^{1/3}\ (\mathbf{3^*},\mathbf{1},\mathbf{1},2/3)$$

It is clearly anomaly free.

The Higgs Sector

In the Higgs sector we have:

- A left doublet χ_L (**1**,**2**,**1**,1) and its CP-mirror $\tilde{\chi}_R$ (**1**,**1**,**2***,1,-1), and their SU(2) rotated counterpart $\tilde{\chi}_L = i\sigma_2\chi_L^*$ (**1**,**2***,**1**,-1), and χ_R (**1**,**1**,**2**,1).
- A singlet Higgs scalar ϕ (**1**,**1**,**1**,0), whose *CP*-mirror partner is itself, but transform as $\phi \rightarrow -\phi$ (Necessary to break L-R).
- A leptoquark singlet scalar ρ (**3**,**1**,**1**,-2/3) with its *CP*-mirror partner $\tilde{\rho}$ (**3***,**1**,**1**,2/3) (which is equal to its h.c).
- Unlike in the usual LR model, there is no bidoublet (Thus there is no tree level W_L/W_R mixing.)

Higgs Potential

A general Higgs potensial, invariant under the gauge and the CP-mirroring is

$$\begin{aligned} V &= -\mu_1^2|\phi|^2 - \mu_2^2(|\chi_L|^2 + |\chi_R|^2) + \mu_3^2|\rho|^2 + \lambda_1|\phi|^4 \\ &+ \lambda_2(|\chi_L|^4 + |\chi_R|^4) + \lambda_3|\rho|^4 + \lambda_4|\chi_L|^2|\chi_R|^2 \\ &+ \epsilon_1(|\chi_L|^2 + |\chi_R^2)|\phi|^2 + \epsilon_2(|\chi_L|^2 + |\chi_R|^2)|\rho|^2 \\ &+ \epsilon_3|\rho|^2|\phi|^2 + (\delta_1\phi(|\chi_L|^2 - |\chi_R|^2) + \text{h.c.}) \end{aligned}$$

The potensial will give the following VEV

$$\langle\chi_L\rangle = \begin{pmatrix} 0 \\ v_L \end{pmatrix}; \qquad \langle\chi_R\rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}, \qquad \langle\phi\rangle = V, \tag{1}$$

(The leptoquark ρ will not acquire VEV)

The VEV fulfill the extremum condition

$$-(\mu_2^2 - \epsilon_1 V) + 2\lambda_2 v_L^2 + \lambda_4 v_R^2 + \delta_1 V = 0 \tag{2}$$

$$-(\mu_2^2 - \epsilon_1 V) + 2\lambda_2 v_R^2 + \lambda_4 v_L^2 - \delta_1 V = 0 \tag{3}$$

$$-2\mu_1^2 V + 4\lambda_1 V^3 + 2\epsilon_1 (v_L^2 + v_R^2) V + \delta_1 (v_L^2 - v_R^2) = 0 \tag{4}$$

which gives

$$v_L = \sqrt{\frac{(\mu_2^2 - \epsilon_1 V)}{(2\lambda_2 + \lambda_4)} - \frac{\delta_1 V}{2\lambda_2 - \lambda_4}} \tag{5}$$

$$v_R = \sqrt{\frac{(\mu_2^2 - \epsilon_1 V)}{(2\lambda_2 + \lambda_4)} + \frac{\delta_1 V}{2\lambda_2 - \lambda_4}} \tag{6}$$

Thus for $V \neq 0$, it is possible to have $v_R > v_L$.

Weak Gauge Boson

Similar to the usual LRS model, especially for model without bidoublet and only v_L and v_R contribution to $W_{L/R}$ masses,

- Masses of the charged weak bosons:

$$M_{W_L}^2 = \frac{1}{4}g^2 v_L^2; \quad M_{W_R}^2 = \frac{1}{4}g^2 v_R^2. \tag{7}$$

  (No bidoublet, no W_L/W_R mixing at tree level).

- For the neutral weak boson:

$$M_Z^2 = \frac{1}{4}\frac{v_L^2 g^2}{\cos^2\theta_W}\left(1 - \omega^2 \sin^4\beta\right) \tag{8}$$

$$M_{Z'}^2 = \frac{1}{4}v_R^2 g^2 \tan^2\theta_W \tan^2\beta\left(1 + \frac{\omega^2 \sin^2 2\beta}{4\sin^2\theta_W}\right) \tag{9}$$

  where $\omega = v_L/v_R$ and the mixing angle

$$\sin^2\theta_W = \frac{g^2 g'^2}{g^4 + 2g^2 g'^2}; \quad \sin^2\beta = \frac{g'^2}{g^2 + g'^2}. \tag{10}$$

Yukawa Interaction

The Yukawa interaction (suppressing generation index)

$$\begin{aligned}\mathcal{L} &= -G_e(\bar{l}_L\chi_L e_R + \bar{L}_R\tilde{\chi}_R E_L) - G_\nu(\bar{l}_L\tilde{\chi}_L\nu_{1R} + \bar{L}_R\chi_R\nu_{1L}) \\ &- G_d(\bar{q}_L\chi_L d_R + \bar{Q}_R\tilde{\chi}_R D_L) - G_u(\bar{q}_L\tilde{\chi}_L u_R + \bar{Q}_R\chi_R U_L) \\ &- G_{d\nu}(\bar{D}_L\rho^\dagger\nu_{1R} + \bar{d}_R\rho\nu_{1L}) - G_{ue}(\bar{U}_L\rho^\dagger e_R + \bar{u}_R\rho E_L) - M\bar{\nu}_{1R}\nu_{1L} \\ &+ \text{h.c.} \qquad (11)\end{aligned}$$

The following possible Yukawa interactions do not respect fermion number conservation,

$$\begin{aligned}&- G'_e(\bar{l}_L\chi_L E^c_L + \bar{l}_R\tilde{\chi}_R e^c_R) - G'_\nu(\bar{l}_L\tilde{\chi}_L\nu^c_{1L} + \bar{l}_R\chi_R\nu^c_{1R}) \\ &- G'_{d\nu}(\bar{D}_L\tilde{\rho}\nu^c_{1L} + \bar{d}_R\rho\nu^c_{2R}) - G'_{ue}(\bar{U}_L\tilde{\rho}E^c_L + \bar{u}_R\rho e^c_R) \\ &- G_{du}(\bar{D}^c_L\tilde{\rho}U_L + \bar{d}^c_R\rho u_R) + M_M(\bar{\nu}_{1R}\nu^c_{1R} + \bar{\nu}_{1L}\nu^c_{1L}) \\ &+ \text{h.c.} \qquad (12)\end{aligned}$$

$\longrightarrow$ proton decays, non chiral pion decay, and lepton number violation in the charge lepton sector, etc. $\rightarrow$ I chose to impose fermion number conservation (No Majorana neutrino).

Quark and Lepton Masses

The Lagrangian which is relevant for the quark and the charged lepton (and their CP-mirror) masses (after SSB) is

$$\begin{aligned} &- G_d(v_L\bar{d}_L d_R + v_R\bar{D}_R D_L) - G_u(v_L\bar{u}_L u_R + v_R\bar{U}_R U_L) \\ &- G_e(v_L\bar{e}_L e_R + v_R\bar{E}_R E_L) + \text{h.c.} \end{aligned} \qquad (13)$$

- Thus the quarks and the charged leptons would obtain masses as in the SM.
- while the CP-mirror quarks and charged lepton, U, D and E, will have very heavy masses v_R/v_L times the masses of its SM counterpart.
- The same CKM matrix can also occur in the mirror quark sector, therefore like in the SM, the higher generation mirror particles will decay into the first generation mirror particles, through the W_R.

Neutrino Mass

The Lagrangian which is relevant for neutrino mass (after SSB) is

$$-G_\nu(v_L\bar{\nu}_{2L}\nu_{1R} + v_R\bar{\nu}_{2R}\nu_{1L}) - M\bar{\nu}_{1R}\nu_{1L} + \text{h.c.} \tag{14}$$

from which we have the following mass matrix

$$\begin{array}{c} \\ \bar{\nu}_{1L} \\ \bar{\nu}_{1R} \\ \bar{\nu}_{2L} \\ \bar{\nu}_{2R} \end{array} \begin{array}{c} \begin{array}{cccc} \nu_{1L} & \nu_{1R} & \nu_{2L} & \nu_{2R} \end{array} \\ \begin{pmatrix} 0 & M & 0 & G_\nu v_R \\ M & 0 & G_\nu v_L & 0 \\ 0 & G_\nu v_L & 0 & 0 \\ G_\nu v_R & 0 & 0 & 0 \end{pmatrix} \end{array} \tag{15}$$

Similar like the one in [M. Roncadelli1, D. Wyler, Phys. Lett. **B 133**, 5, 325-329.] Assuming that M is very large, this mass matrix will lead to a type-1 Dirac seesaw like mechanism. Diagonalizing, we have one small mass and one large mass.

The four Weyl spinor paired up into two quasi Dirac spinors

$$\nu \approx \nu_{2L} + \nu_{2R} - \frac{G_\nu v_L}{M}\nu_{1L} - \frac{G_\nu v_R}{M}\nu_{1R} \tag{16}$$

$$N \approx \nu_{1L} + \nu_{1R} + \frac{G_\nu v_L}{M}\nu_{2L} + \frac{G_\nu v_R}{M}\nu_{2R} \tag{17}$$

whose masses are

$$m_\nu \approx \frac{G_\nu^2 v_L v_R}{M}; \quad m_N \approx M \tag{18}$$

The light neutrino is dominated by the doublet neutrino, while the heavy neutrino is dominated by the singlet neutrino.

Order of Magnitude Calculation on M

- Assume G_ν is of the order of the charged lepton Yukawa coupling $G_e \propto 10^{-6}$.
- Assume $v_R \propto 10^2 v_L$ (The current bound on ω gives $v_R > 30 v_L$).
- If $m_\nu \propto$ eV - meV, then from

$$m_\nu \approx \frac{(10^{-6})^2 v_L^2 10^2}{M}$$

we have $M \propto 1 - 1000$ TeV.

Problems in dissapearing the heavy CP-mirror particles

$$-G_{d\nu}(\bar{D}_L\rho^\dagger\nu_{1R} + \bar{d}_R\rho\nu_{1L}) - G_{ue}(\bar{U}_L\rho^\dagger e_R + \bar{u}_R\rho E_L) + \text{h.c.} \qquad (19)$$

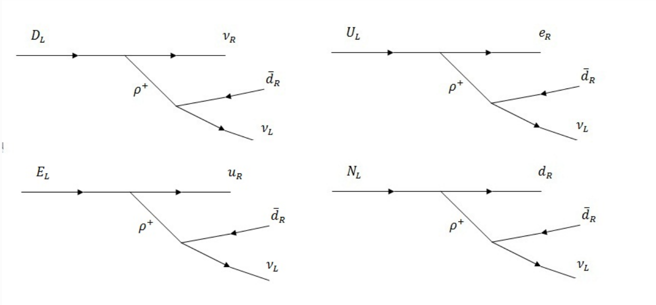

Figure: Heavy CP-Mirror Particles Decay through leptoquark I

Decay of the Heavy CP-Mirror Particles

Possible decay

$$\begin{aligned}
D_L &\rightarrow \nu_R + \nu_L + \bar{d}_R \quad \Gamma \propto G_{d\nu}^4 \left(\frac{G_\nu v_L}{M}\right)^2 \frac{m_D^5}{m_\rho^4} \\
U_L &\rightarrow e_R + \nu_L + \bar{d}_R \quad \Gamma \propto G_{ue}^2 G_{d\nu}^2 \left(\frac{G_\nu v_L}{M}\right)^2 \frac{m_U^5}{m_\rho^4} \\
E_L &\rightarrow u_R + \nu_L + \bar{d}_R \quad \Gamma \propto G_{ue}^2 G_{d\nu}^2 \left(\frac{G_\nu v_L}{M}\right)^2 \frac{m_E^5}{m_\rho^4} \\
N_L &\rightarrow d_R + \nu_L + \bar{d}_R \quad \Gamma \propto G_{d\nu}^4 \left(\frac{G_\nu v_L}{M}\right)^2 \frac{m_N^5}{m_\rho^4}
\end{aligned} \tag{20}$$

where m_ρ is the mass of the leptoquark scalar. These decays are very slow ! Except if mass of the mirror particles are very large compare to the mass of the leptoquark.

Decay or the Heavy CP-Mirror Particles

Another Possibility

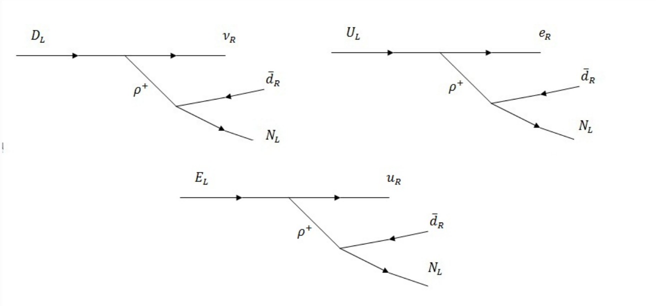

Figure: Heavy CP-Mirror Particles Decay through leptoquark II

But this is only happen if N is lightest mirror particle, which is not the case.

Scattering off Heavy CP-Mirror Particles

There are several possible scattering process that will scattered off the heavy CP-mirror particles:

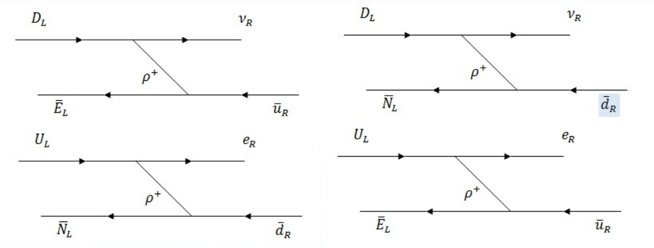

Figure: Scattering off the Heavy CP-particles

But it occurs only between the CP-Mirror and its antiparticles. Thus it should take place before the baryon assymmetry occur.

Summary

- A model based on the $SU(3)\otimes SU(2)_L\otimes SU(2)_R\otimes U(1)_I$ gauge, with CP-mirror particles has been built.
- In the quark and charged lepton sectors, the CP-mirror particles are v_R/v_L times heavier than the SM partner, but with the same mass spectrum.
- The mass of the neutrino is through type-I Dirac seesaw, and we have very light neutrinos ν and very heavy neutrinos N.
- There are problems in the heavy CP-mirror particles decay into SM particles. But we could also scattered away the heavy CP-mirror particles, before the baryon assymmetry takes place.
- Still on going work, would appreciate any comments.

THANK YOU