Eur. Phys. J. C (2014) 74:3078
DOI 10.1140/epjc/s10052-014-3078-x

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Post-sphaleron baryogenesis and n–$\bar{n}$ oscillation in non-SUSY SO(10) GUT with gauge coupling unification and proton decay

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Received: 30 May 2014 / Accepted: 15 September 2014 / Published online: 30 September 2014

Abstract "Post-sphaleron baryogenesis", a fresh and profound mechanism of baryogenesis accounts for the matter–antimatter asymmetry of our present universe in a framework of Pati–Salam symmetry. We attempt here to embed this mechanism in a non-SUSY SO(10) grand unified theory by reviving a novel symmetry breaking chain with Pati–Salam symmetry as an intermediate symmetry breaking step and as well to address post-sphaleron baryogenesis and neutron–antineutron oscillation in a rational manner. The Pati–Salam symmetry based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_C$ is realized in our model at 10^5–10^6 GeV and the mixing time for the neutron–antineutron oscillation process having $\Delta B = 2$ is found to be $\tau_{n-\bar{n}} \simeq 10^8$–$10^{10}$ s with the model parameters, which is within the reach of forthcoming experiments. Other novel features of the model include low scale right-handed $W_R^{\pm}$, Z_R gauge bosons, explanation for neutrino oscillation data via the gauged inverse (or extended) seesaw mechanism and most importantly TeV scale color sextet scalar particles responsible for an observable n–$\bar{n}$ oscillation which may be accessible to LHC. We also look after gauge coupling unification and an estimation of the proton lifetime with and without the addition of color sextet scalars.

1 Introduction

The Standard Model (SM) of particle physics has given us enough reasons to look beyond its framework for dealing with issues like the tiny neutrino masses, matter–antimatter asymmetry of the present universe, dark matter and dark energy, and coupling unification of three fundamental interactions. Among all these, the observed baryon asymmetry of the universe has motivated the scientific community to work upon it since a long time ago. The WMAP satellite data [1,2], when combined with large scale structure (LSS) data, gives a baryon asymmetry of the universe of $\eta^{\rm CMB} \simeq (6.3 \pm 0.3) \times 10^{-10}$, while an independent measurement of the baryon asymmetry carried out by BBN [3] yields $\eta^{\rm BBN} \simeq (3.4 - 6.9) \times 10^{-10}$. Two compelling mechanisms, namely leptogenesis [4] and weak scale baryogenesis [5], have been prime tools for explaining the baryon asymmetry of the universe. In leptogenesis the desired lepton asymmetry is created by the lepton number violation as well as out of equilibrium decays of heavy particles, which is subsequently converted into baryon asymmetry by the non-perturbative $(B + L)$-violating sphaleron interactions [6,7].

Inadequate knowledge of the nature of new physics beyond the standard model leaves us with no choice but to explore all possibilities which may explain the origin of the matter–antimatter asymmetry. Recently a new idea behind baryon asymmetry has been explored named "Post-Sphaleron Baryogenesis (PSB)", which occurs via the decay of a scalar boson singlet for the standard model having a mass around a few hundreds of GeV and a high dimensional baryon number violating coupling [8–10], where the Yukawa coupling(s) of the scalar(s) act as the source of the CP asymmetry. Apparently, this high dimensional baryon number violating coupling is generated via new physics operative beyond standard model electroweak theory. The mechanism of PSB is based on the idea that the required amount of baryon asymmetry of the universe can be generated below the scale of electroweak phase transition where the sphaleron has decoupled from the Hubble expansion rate. Although the proposal seems interesting it has not yet been incorporated in a realistic grand unified theory. Hence we attempt here to embed the proposal of PSB in a non-SUSY SO(10) GUT with Pati–Salam (PS) symmetry and left–right (LR) symmetry as intermediate symmetry breaking steps.

A detailed study of the literature [11–18] gives an idea of many intriguing features of the SO(10) grand unified theory (including both non-SUSY and SUSY). One of these features is that when a left–right gauge symmetry appears

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as an intermediate symmetry breaking step in a novel symmetry breaking chain, then the seesaw mechanism can be naturally incorporated into it. In conventional seesaw models associated with thermal leptogenesis the mass scale for heavy RH Majorana neutrino is at 10^{10} GeV, which makes it unsuitable for direct detectability at current accelerator experiments like LHC. Therefore, it is necessary to construct a theory having $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)_{B-L} \times SU(3)_C$ and $SU(2)_L \times \mathrm{SU}(2)_R \times \mathrm{SU}(4)_C$ gauge groups as intermediate symmetry breaking steps, which results in low mass right-handed Majorana neutrinos along with W_R, Z' gauge bosons at the TeV scale. At the same time it should be capable of explaining post-sphaleron baryogenesis elegantly along with other derivable predictions like proton decay and neutron–antineutron oscillation.

We intend to discuss TeV scale post-sphaleron baryogenesis, the neutron–antineutron oscillation having a mixing time close to the experimental limit with the Pati–Salam symmetry or SO(10) GUT as mentioned in a recent work [19] slightly modifying the Higgs content, where nonzero light neutrino masses can be accommodated via the gauged extended inverse seesaw mechanism along with TeV scale W_R, Z' gauge bosons. As discussed in the work [19] the Dirac neutrino mass matrix is similar to the up-quark mass matrix even with low scale right-handed symmetry breaking. Though the details has been already discussed in the above mentioned work we briefly clarify the point as follows.

In non-SUSY SO(10), the type I seesaw [20–24] contribution to neutrino mass is given by

$$m_\nu^I = -M_D M_R^{-1} M_D^{\mathrm{T}},$$

where M_D is the Dirac neutrino mass matrix, M_R is the Majorana neutrino mass matrix for right-handed neutrinos and is related to the right-handed symmetry breaking scale. The Dirac neutrino mass matrix and up-quark mass matrices are similar in a generic SO(10) model that has high scale Pati–Salam symmetry as an intermediate breaking step relating quarks and leptons with each other. Hence, $M_D \simeq M_u$, which further implies that the τ-neutrino Dirac Yukawa coupling should be equal to the top-quark Yukawa coupling. With $M_D \simeq M_u \simeq 100$ GeV, the sub-eV scale of the light neutrino consistent with the oscillation data requires the right-handed scale (seesaw scale) to be greater than 10^{13} GeV. Such a high seesaw scale makes this idea difficult to probe at any foreseeable laboratory experiments. Hence, as an alternative way, emphasizing its verifiability at LHC, the inverse seesaw mechanism [25–27] has been proposed, with an extra SO(10) fermion singlet S (in addition to the existing fermion content of SO(10)), with a light neutrino mass formula

$$m_\nu = \left(\frac{M_D}{M}\right) \mu \left(\frac{M_D}{M}\right)^{\mathrm{T}},$$

where M is the N–S mixing matrix and μ is the small lepton number violating mass term for sterile neutrino S. The above relation can be recast as

$$\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right) = \left(\frac{M_D}{100\,\mathrm{GeV}}\right)^2 \left(\frac{\mu}{\mathrm{keV}}\right) \left(\frac{M}{10^4\,\mathrm{GeV}}\right)^{-2}.$$

Hence, sub-eV masses for the light neutrinos are consistent with $M_D \simeq M_u$ (or $Y_D \simeq Y_t$) which is a generic predictions of high scale Pati–Salam symmetry and compatible with low right-handed symmetry breaking scale (M_R), since the inverse seesaw formula is independent of M_R. We have utilized this particular property of low scale right-handed symmetry breaking in studying post-sphaleron baryogenesis and neutron–antineutron oscillation even though a complete discussion on the origin of neutrino masses and mixing via low scale extended inverse seesaw has been omitted.

Here we sketch out the complete work of our paper. In Sect. 2, we briefly discuss non-SUSY SO(10) GUT with a novel symmetry breaking chain, having $\mathcal{G}_{2213}$ and $\mathcal{G}_{224}$ as intermediate symmetry breaking steps. In Sect. 3 we show how gauge coupling unification is achieved in our model. In Sect. 4 we discuss the TeV scale post-sphaleron baryogenesis and embed it within the novel chain of a non-SUSY SO(10) model with self-consistent model parameters. In Sect. 5, we estimate the mixing time for the neutron–antineutron oscillation. In Sect. 6, we present an idea of how low mass scales for the RH Majorana neutrino as well as right-handed gauge bosons W_R, Z' are allowed in the model, while explaining light neutrino masses via a gauged extended seesaw mechanism. In Sect. 7 we conclude our work with results and a summary, including a note on the viability of the model at LHC.

2 The model

In this section we shall discuss the one-loop gauge coupling unification and estimate the proton life time including short distance enhancement factor to the $d = 6$ proton decay operator by reviving the symmetry breaking chain [19]

$$\begin{aligned}
\mathrm{SO}(10) &\xrightarrow{M_U} \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{SU}(4)_C D \\
&\quad \times [\mathcal{G}_{224D},\ (g_{2L} = g_{2R})] \\
&\xrightarrow{M_P} \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{SU}(4)_C \quad [\mathcal{G}_{224}, (g_{2L} \neq g_{2R})] \\
&\xrightarrow{M_C} \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)_{B-L} \times \mathrm{SU}(3)_C \quad [\mathcal{G}_{2213}] \\
&\xrightarrow{M_\Omega} \mathrm{SU}(2)_L \times U(1)_R \times U(1)_{B-L} \times \mathrm{SU}(3)_C \quad [\mathcal{G}_{2113}] \\
&\xrightarrow{M_{B-L}} \mathrm{SU}(2)_L \times U(1)_Y \times \mathrm{SU}(3)_C \quad [\mathcal{G}_{\mathrm{SM}} \equiv \mathcal{G}_{213}] \\
&\xrightarrow{M_Z} U(1)_{\mathrm{em}} \times \mathrm{SU}(3)_C \quad [\mathcal{G}_{13}]. \qquad (1)
\end{aligned}$$

The chain breaks in a sequence, where SO(10) first breaks down to $\mathcal{G}_{224D}$, $(g_{2L} = g_{2R})$ after the Higgs representation

$\langle(1,1,1)\rangle \subset \{54\}_H$ is given a VEV, then the spontaneous breakdown of D-parity occurs in $\mathcal{G}_{224D}, (g_{2L} = g_{2R}) \to \mathcal{G}_{224}, (g_{2L} \neq g_{2R})$ with the assignment of a VEV to the D-parity odd component $\langle(1,1,1)\rangle$ contained in the Higgs representation $\{210\}_H$. The decomposition of $\{210\}_H$ under $\mathcal{G}_{224}$ is

$$\{210\}_H = (1,1,1) \oplus (2,2,20) \oplus (3,1,15) \oplus (1,3,15) \oplus (2,2,6) \oplus (1,1,15). \quad (2)$$

Spontaneous D-parity mechanism is aptly utilized here, since the theory allows low mass scale for right-handed Higgs fields around $\mathcal{O}$(TeV), while keeping all its left-handed components at D-parity breaking scale. Now assigning a VEV to the neutral component $\langle(1,1,15)\rangle \subset \{210\}_H$, the Pati–Salam symmetry ($\mathcal{G}_{224}$) breaks down to the left–right symmetry ($\mathcal{G}_{2213}$). The next step of symmetry breaking $\mathcal{G}_{2213} \to \mathcal{G}_{2113}$ occurs via the VEV $\langle(1,3,0,1)\rangle \subset \{210\}_H$. The right-handed gauge boson W_R acquires a mass in the range of a few TeV and contributes sub-dominantly to neutrinoless double beta decay.

The most desirable symmetry breaking step $\mathcal{G}_{2113} \to \mathcal{G}_{213}$ is achieved by the $\{126\}_H$ of SO(10) though we have added another Higgs representation $\{16\}_H$ for realization of the gauged inverse seesaw mechanism operative at the TeV scale. The decomposition of the Higgs $\{126\}_H$ under $\mathcal{G}_{224}$ is

$$\{126\}_H = (3,1,10) \oplus (1,3,\overline{10}) \oplus (2,2,15) \oplus (1,1,6). \quad (3)$$

As we have pointed earlier, due to the D-parity mechanism, the right-handed triplet Higgs field $\Delta_R(1,3,-2,1)$ contained in (3, 1, 10) gets its mass at the TeV scale, while its left-handed partner $\Delta_L(3,1,-2,1)$ has its mass at D-parity breaking scale M_P. As a result of this symmetry breaking, the neutral component of the right-handed gauge boson Z' gets its mass around $\mathcal{O}$(TeV) with the experimental bound $M_{W_R} \geq 2.5$ TeV [30,31]. The final stage of symmetry breaking $\mathcal{G}_{2113} \to \mathcal{G}_{213}$ is carried out by giving a VEV to the neutral component of SM Higgs doublet $\langle\phi^0(2,1/2,1)\rangle$ contained in the bidoublet $\Phi \subset \{10\}_H$.

We shall now check whether SO(10) having TeV scale post-sphaleron baryogenesis, neutron–antineutron oscillation and the gauged inverse seesaw mechanism is consistent with gauge coupling unification. It is found that the coupling constants unify at (10^{17}–$10^{18.5}$) GeV with the Higgs fields $\{10\}_H + \{10\}'_H + \{16\}_H + \{126\}_H + \{210\}_H$. Some good reasons behind taking these Higgs fields are as follows. First, the TeV scale post-sphaleron baryogenesis and neutron–antineutron oscillation can be well explained with these parameters, while predicting a W_R gauge boson in the TeV range. Second, it allows $B-L$ breaking (M_{B-L}) at the TeV scale resulting in a Z' mass $\geq$ 1.6 TeV; moreover, it explains tiny masses for light neutrinos consistent with neutrino oscillation data via the TeV scale gauged inverse seesaw mechanism and LFV decays with branching ratios accessible to ongoing search experiments.

3 Gauge coupling unification and proton decay

3.1 One-loop renormalization group equations (RGEs) for gauge coupling evolution

For simplicity, we consider only the one-loop renormalization group equations (RGEs) for gauge coupling evolution, which can be written as

$$\mu \frac{\mathrm{d}\, g_i}{\mathrm{d}\, \mu} = \frac{a_i}{16\pi^2} g_i^3 \implies \frac{\mathrm{d}\, \alpha_i^{-1}}{\mathrm{d}\, t} = \frac{\boldsymbol{a_i}}{2\pi} \quad (4)$$

where $t = \ln(\mu)$, $\alpha_i = g_i^2/(4\pi)$ is the fine structure constant, and $\boldsymbol{a_i}$ is for the one-loop beta coefficients derived for the corresponding ith gauge group for which coupling evolution has to be determined. Using the input parameters, the electroweak mixing angle $\sin^2\theta_W(M_Z) = 0.2312$, the electromagnetic coupling constant $\alpha(M_Z) = 127.9$ and the strong coupling constant $\alpha_S(M_Z) = 0.1187$ taken from PDG [3,28,29], the values of the three coupling constants at the electroweak scale $M_Z = 91.187$ GeV can be calculated precisely to be

$$\begin{pmatrix} \alpha_{2L}(M_Z) \\ \alpha_{1Y}(M_Z) \\ \alpha_{3C}(M_Z) \end{pmatrix} = \begin{pmatrix} 0.033493^{+0.000042}_{-0.000038} \\ 0.016829 \pm 0.000017 \\ 0.118 \pm 0.003 \end{pmatrix}, \quad (5)$$

where $\{\alpha_{2L}(M_Z), \alpha_{1Y}(M_Z), \alpha_{3C}(M_Z)\}$ denote the fine structure constants for the SM gauge group $\mathcal{G}_{213} = \mathrm{SU}(2)_L \times U(1)_Y \times \mathrm{SU}(3)_C$.

3.2 Higgs content for the model and corresponding one-loop beta coefficients $\boldsymbol{a_i}$

The Higgs contents for the model used in different ranges of the mass scales under respective gauge symmetries ($\mathcal{G}_I$) with a particular symmetry breaking chain as considered in a recent work [19] where the prime interest was to keep the W_R, Z_R gauge bosons at the TeV scale are as follows:

(i) $\mu = \mathbf{M_Z} - \mathbf{M_{B-L}} : G = \mathrm{SM} = G_{213}$,
Higgs: $\Phi(2,1/2,1)$;

(ii) $\mu = \mathbf{M_{B-L}} - \mathbf{M_\Omega} : G = G_{2113}$,
Higgs: $\Phi_1(2,1/2,0,1) \oplus \Phi_2(2,-1/2,0,1) \oplus \chi_R(1,1/2,-1,1) \oplus \Delta_R(1,1,-2,1)$;

(iii) $\mu = \mathbf{M_\Omega} - \mathbf{M_C} : G = G_{2213}$,
Higgs: $\Phi_1(2,2,0,1) \oplus \Phi_2(2,2,0,1) \oplus \chi_R(1,2,-1,1) \oplus \Delta_R(1,3,-2,1) \oplus \Omega_R(1,3,0,1)$, (6)

(iv) $\mu = \mathbf{M_C} - \mathbf{M_\xi} : G = G_{224}$,

Higgs: $\Phi_1(2,2,1)_{10} \oplus \Phi_2(2,2,1)_{10'} \oplus \Delta_R(1,3,\overline{10})_{126}$
$\oplus \chi_R(1,2,\bar{4})_{16}$
$\oplus \Omega_R(1,3,15)_{210} \oplus \Sigma(1,1,15)_{210}$,

(v) $\mu = \mathbf{M_\xi} - \mathbf{M_P} : G = G'_{224}$,

Higgs: $\Phi_1(2,2,1)_{10} \oplus \Phi_2(2,2,1)_{10'} \oplus \Delta_R(1,3,\overline{10})_{126}$
$\oplus \chi_R(1,2,\bar{4})_{16} \oplus \Omega_R(1,3,15)_{210}$
$\oplus \Sigma(1,1,15)_{210} \oplus \xi(2,2,15)_{126}$,

(vi) $\mu = \mathbf{M_P} - \mathbf{M_U} : G = G_{224D}$,

Higgs: $\Phi_1(2,2,1)_{10} \oplus \Phi_2(2,2,1)_{10'} \oplus \Delta_L(3,1,10)_{126}$
$\oplus \Delta_R(1,3,\overline{10})_{126} \oplus \chi_L(2,1,4)_{16} \oplus \chi_R(1,2,\bar{4})_{16}$
$\oplus \Omega_L(3,1,15)_{210} \oplus \Omega_R(1,3,15)_{210}$
$\oplus \Sigma(1,1,15)_{210} \oplus \xi(2,2,15)_{126} \oplus \sigma(1,1,1)_{210}$. (7)

Here we find two categories of Higgs spectrum: Model I having Higgs spectrum as given in Eqs. (6) and (7) excluding the bitriplet Higgs scalar which estimates a proton life time that is far from the reach of search experiments and Model II having the same Higgs spectrum, including the bitriplet Higgs scalar $(3,3,1) \subset \mathcal{G}_{224}$ from the mass scale M_C onwards, which estimates a proton life time very close to the experimental limit. Thus Model II serves our purpose.

The one-loop beta coefficients are found to be the same for both models at the mass scale ranges M_Z–M_{B-L}, M_{B-L}–M_Ω, and M_Ω–M_C i.e.,

(i) $\mu = \mathbf{M_Z} - \mathbf{M_{B-L}} : G = \mathrm{SM} = G_{2_L 1_Y 3_C}$,
$\boldsymbol{a_i} = (-19/6,\ 41/10,\ -7)$,

(ii) $\mu = \mathbf{M_{B-L}} - \mathbf{M_\Omega} : G = G_{2_L 1_R 1_{(B-L)} 3_C}$,
$\boldsymbol{a_i} = (-3,\ 19/4,\ 37/8,\ -7)$,

(iii) $\mu = \mathbf{M_\Omega} - \mathbf{M_C} : G = G_{2_L 2_R 1_{(B-L)} 3_C}$,
$\boldsymbol{a_i} = (-8/3,\ -2/3,\ 23/4,\ -7)$, (8)

whereas they differ at the Pati–Salam scale M_C to the unification scale M_U as shown in Table 1.

The gauge coupling unification for this work is shown in Fig. 1 with the allowed mass scales desirable for our model predictions,

$$M_{B-L} = 4 - 7\ \mathrm{TeV},\ M_\Omega = 10\ \mathrm{TeV},\ M_C = 10^5 - 10^6\ \mathrm{GeV},$$
$$M_P \simeq 10^{15.65}\ \mathrm{GeV\ and}\ M_G \simeq 10^{18.65}\ \mathrm{GeV}. \quad (9)$$

3.3 Estimation of proton life time for $p \to \pi^0 e^+$

The decay rate for the gauge boson mediated proton decay in the channel $p \to \pi^0 e^+$ including strong and electroweak renormalization effects on the d = 6 operator starting from the GUT scale to the proton mass (i.e., 1 GeV) [32,33] turns out to be

Table 1 One-loop beta coefficients for different gauge coupling evolutions, without bitriplet Higgs scalar in Model I and with a bitriplet Higgs scalar (3, 3, 1) under the Pati–Salam group $SU(2)_L \times SU(2)_R \times SU(4)_C$ in Model II

G_I	Mass ranges	$\boldsymbol{a_i}$ for Model I	$\boldsymbol{a_i}$ for Model II
$G_{2_L 2_R 4_C}$	$M_C - M_\xi$	$\begin{pmatrix}-8/3\\29/3\\-14/3\end{pmatrix}$	$\begin{pmatrix}-2/3\\35/2\\-14/3\end{pmatrix}$
$G_{2_L 2_R 4_C}$	$M_\xi - M_P$	$\begin{pmatrix}7/3\\44/3\\2/3\end{pmatrix}$	$\begin{pmatrix}-12/3\\35/3\\-14/3\end{pmatrix}$
$G_{2_L 2_R 4_C D}$	$M_P - M_U$	$\begin{pmatrix}44/3\\44/3\\6\end{pmatrix}$	$\begin{pmatrix}35/3\\35/3\\2/3\end{pmatrix}$

$$\Gamma(p \to \pi^0 e^+) = \frac{\pi}{4} A_L^2 \frac{|\overline{\alpha}_H|^2}{f_\pi^2} \frac{m_p \alpha_U^2}{M_U^4} (1 + \mathcal{F} + \mathcal{D})^2 \mathcal{R}. \quad (10)$$

In Eq. (10), $A_L = 1.25$ is the renormalization factor from the electroweak scale to the proton mass, $\mathcal{D} = 0.81$, $\mathcal{F} = 0.44$, $\overline{\alpha}_H = -0.011\ \mathrm{GeV}^3$, and $f_\pi = 139$ MeV, which have been extracted as phenomenological parameters by the chiral perturbation theory and lattice gauge theory. Also $m_p = 938.3$ MeV is the proton mass, and $\alpha_U \equiv \alpha_G$ is the gauge fine structure constant derived at the GUT scale. It is worth to note here that the renormalization factor $\mathcal{R} = [(A_{SR}^2 + A_{SL}^2)(1+|V_{ud}|^2)^2]$ for SO(10), $V_{ud} = 0.974 =$ with $A_{SL}(A_{SR})$ being the short-distance renormalization factor in the left (right) sectors, and V_{ud} is the (1, 1) element of V_{CKM} for quark mixings.

After re-expressing $\alpha_H = \overline{\alpha}_H(1+\mathcal{F}+\mathcal{D}) = 0.012\ \mathrm{GeV}^3$, and $\mathcal{A}_R \simeq \mathcal{A}_L \mathcal{A}_{SL} \simeq \mathcal{A}_L \mathcal{A}_{SR}$, the proton life time can be expressed as

$$\tau_p = \Gamma^{-1}(p \to \pi^0 e^+) = \frac{4}{\pi} \frac{f_\pi^2}{m_p} \frac{M_U^4}{\alpha_U^2} \frac{1}{\alpha_H^2 \mathcal{A}_R^2} \frac{1}{\mathcal{F}_q}, \quad (11)$$

where $\mathcal{F}_q \simeq 7.6$.

Short-distance enhancement factor $\mathcal{A}_{\mathbf{SL}}$ extrapolated from GUT scale to **1** GeV: For estimating the proton decay rate in the channel $p \to e^+ \pi^0$ having a dimension-6 operator, one needs to extrapolate the operator from the GUT-scale physics to low energy physics at the scale of $m_p = 1$ GeV [34–36]. With the particular symmetry breaking chain allowed in the non-SUSY SO(10) model (following Ref. [36]), the whole energy range can be separated into the following parts:

I. from non-SUSY S0(10) GUT scale, M_U, to the Pati–Salam symmetry with D-parity ($\mathcal{G}_{224D}$, $g_{2L} = g_{2R}$) invariance scale, M_P,
II. from M_P to the Pati–Salam symmetry without D-parity ($\mathcal{G}_{224}$, $g_{2L} \neq g_{2R}$) scale M_C,

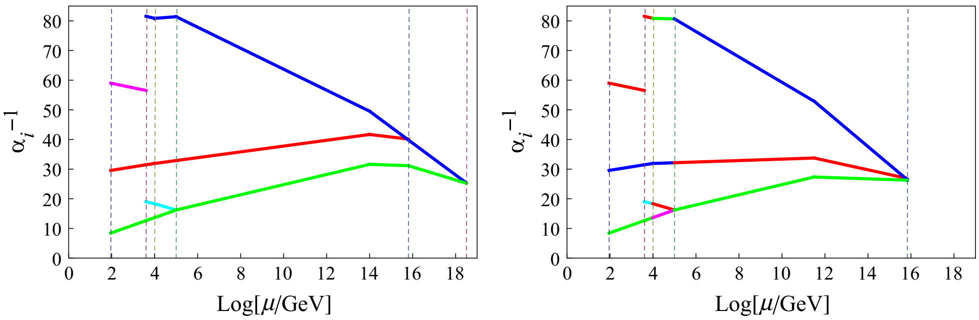


Fig. 1 Gauge coupling evolution plot having TeV scale W_R, Z_R bosons where $M_U = 2.65 \times 10^{15.8}$ GeV

III. from M_C to the SU(4)$_C$ breaking scale, M_Ω, where we have left–right symmetric model (**LRSM**) $\mathcal{G}_{2213}$,
IV. from the left–right symmetry breaking scale (M_Ω) to the $\mathcal{G}_{2113}$ scale (M_{B-L}),
V. from the $\mathcal{G}_{2113}$ scale (M_{B-L}) to the standard model $\mathcal{G}_{213}$,
VI. from the standard model to 1 GeV.

As discussed in Refs. [34–36], the enhancement factor below SM for the $LLLL$ operator is

$$\mathcal{A}'_L = \left[\frac{\alpha_s(1\ \text{GeV})}{\alpha_s(m_t)}\right]^{-\frac{4}{2\cdot(-11+\frac{2}{3}n_f)}},$$

where n_f denotes the number of quark flavors at the particular energy scale of our interest. Neglecting the effect due to α_{2L} and α_Y since their contributions are suppressed as compared to the strong coupling effect α_s, this enhancement factor can be expressed in a more explicit manner as

$$\mathcal{A}'_L = \left[\frac{\alpha_s(1\ \text{GeV})}{\alpha_s(m_c)}\right]^{2/9}\left[\frac{\alpha_s(m_c)}{\alpha_s(m_b)}\right]^{6/25}\left[\frac{\alpha_s(m_b)}{\alpha_s(m_t)}\right]^{6/23}. \tag{12}$$

Since the model considered here is a non-supersymmetric version of the SO(10) GUT, all other enhancement factors can be written in the same way as

$$\mathcal{A}_{SL}^{\text{SM}} = \left[\frac{\alpha_i(m_t)}{\alpha_i(M_R^0)}\right]^{\frac{-\gamma_i}{2a_i}}, \tag{13}$$

with γ_i ($\boldsymbol{a_i}$) as the anomalous dimension (one-loop beta coefficients) for the corresponding gauge group i = SU(2)$_L$, $U(1)_Y$, SU(3)$_C$. Similarly, one can write the enhancement factor valid for $\mathcal{G}_{2113}$, $\mathcal{G}_{2213}$, $\mathcal{G}_{224}$, and $\mathcal{G}_{224D}$ as

$$\mathcal{A}_{SL}^{2113} = \left[\frac{\alpha_i(M_R^0)}{\alpha_i(M_R^+)}\right]^{\frac{-\gamma_i}{2a_i}},$$
with $i = \text{SU}(2)_L,\quad U(1)_R,\ U(1)_{B-L},\ \text{SU}(3)_C$,

$$\mathcal{A}_{SL}^{2213} = \left[\frac{\alpha_i(M_R^+)}{\alpha_i(M_C)}\right]^{\frac{-\gamma_i}{2a_i}},$$
with $i = \text{SU}(2)_L,\quad \text{SU}(2)_R,\ U(1)_{B-L},\ \text{SU}(3)_C$,

$$\mathcal{A}_{SL}^{224} = \left[\frac{\alpha_i(M_C)}{\alpha_i(M_P)}\right]^{\frac{-\gamma_i}{2a_i}},$$
with $i = \text{SU}(2)_L,\quad \text{SU}(2)_R,\ \text{SU}(4)_C$,

$$\mathcal{A}_{SL}^{224D} = \left[\frac{\alpha_i(M_P)}{\alpha_i(M_U)}\right]^{\frac{-\gamma_i}{2a_i}},$$
with $i = \text{SU}(2)_L,\quad \text{SU}(2)_R,\ \text{SU}(4)_C$ with D-parity.

Hence, the complete short-distance enhancement renormalization factor for this $d = 6$ proton decay operator is found to be

$$\mathcal{A}_{SL} = \mathcal{A}_{SL}^{\text{SM}} \cdot \mathcal{A}_{SL}^{2113} \cdot \mathcal{A}_{SL}^{2213} \cdot \mathcal{A}_{SL}^{224} \cdot \mathcal{A}_{SL}^{224D}. \tag{14}$$

We have precisely followed the prescription given in Ref. [34,35] for the derivation of anomalous dimension for the effective $d = 6(LLLL)$ proton decay operator. With a choice of TeV scale particle spectrum used in our model, the unification scale is found to be $M_U = 2.65 \times 10^{18.5}$ GeV for Model I and $M_U = 10^{15.8}$ GeV for Model II. We have estimated the factor $\mathcal{A}_R = \mathcal{A}_L \cdot \mathcal{A}_{SL}$ approximately to be 4.36 with the value of the long distance renormalization factor $A_L = 1.25$, which is the same for both models.

With these input parameters, the model under consideration predicts the proton life time to be

$$\tau(p \to e^+\pi^0) = 2.6 \times 10^{34}\ \text{years},$$

which is closer to the latest Super-Kamiokande experimental bound [37,38]

$$\tau(p \to e^+\pi^0)|_{SK,2011} > 8.2 \times 10^{33}\ \text{years} \tag{15}$$

and aptly supports planned experiments that can reach a bound [39]

$$\tau(p \to e^+\pi^0)|_{HK,2025} > 9.0 \times 10^{34}\ \text{years},$$
$$\tau(p \to e^+\pi^0)|_{HK,2040} > 2.0 \times 10^{35}\ \text{years}. \tag{16}$$

4 TeV scale post-sphaleron baryogenesis

4.1 Basic interaction terms

As already discussed in Sect. 3, the Pati–Salam symmetry survives till few 100 TeV scale playing an important role in the explanation of baryogenesis mechanism and neutron–antineutron oscillation. We need to know all the basic interactions using quarks and diquarks under the high scale Pati–Salam symmetry as well as under low scale SM-like interactions around the TeV scale in order to explain the above phenomena successfully. For that, we take a look at the decomposition of the Pati–Salam Higgs representation $\Delta_R(1,3,\overline{10})$ under the left–right symmetry group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$ and the SM gauge group $SU(2)_L \times U(1)_Y \times SU(3)_C$,

$$\begin{aligned}
&\Delta(1,3,\overline{10}) = \{\Delta_{\ell\ell}(1,3,-2,1) \oplus \Delta_{q\ell}(1,3,-2/3,3^*) \\
&\oplus\Delta_{qq}(1,3,2/3,6^*) \quad \text{under } \mathcal{G}_{2_L 2_R 1_{B-L} 3_C}, \qquad (17)\\
&\Delta(1,3,\overline{10}) \supset \Delta_{\nu\nu}(1,0,1) \oplus \Delta_{\nu e}(1,1,1) \oplus \Delta_{ee}(1,2,1) \\
&\qquad \oplus\Delta_{u\nu}(1,-2/3,3^*) \oplus \Delta_{de}(1,1/3,3^*) \\
&\qquad \oplus\Delta_{ue}(1,1/3,3^*) \oplus \Delta_{d\nu}(1,1/3,3^*) \\
&\qquad \oplus\Delta_{uu}(1,-4/3,6^*) \oplus \Delta_{ud}(1,-1/3,6^*) \\
&\qquad \oplus\Delta_{dd}(1,2/3,6^*) \quad \text{under } \mathcal{G}_{2_L 1_Y 3_C}, \qquad (18)
\end{aligned}$$

where the electric charge is expressed in terms of the generators of the SM group and left–right symmetric group by

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2} = T_{3L} + Y. \qquad (19)$$

Since the fields $\Delta_{\nu\nu}$(S), Δ_{uu}, Δ_{ud}, Δ_{ud} and quark fields are mainly responsible for the nonzero baryon asymmetry and neutron–antineutron oscillation, we need to know the exact interactions among them. The desirable interaction Lagrangian for diquark Higgs scalars with the SM quarks at the TeV scale which will yield an observable neutron–antineutron oscillation and the post-sphaleron baryogenesis is

$$\begin{aligned}
\mathcal{L} \supset\ & \frac{f_{ij}}{2}\,\Delta_{dd} d_i d_j + \frac{h_{ij}}{2}\,\Delta_{uu} u_i u_j + \frac{g_{ij}}{2\sqrt{2}}\Delta_{ud}(u_i d_j + d_i u_j) \\
& + \frac{\lambda}{2}\Delta_{\nu\nu}\Delta_{dd}\Delta_{ud}\Delta_{ud} + \frac{\lambda'}{2}\Delta_{\nu\nu}\Delta_{uu}\Delta_{dd}\Delta_{dd} + \text{h.c.} \\
\subset\ & F\,(\psi^{\rm T}_{Ra}\, C^{-1}\, \tau_2\, \boldsymbol{\tau}\cdot \Delta^{\dagger}_{ab}\, \psi_{Rb} + \text{L} \leftrightarrow \text{R}) \\
& + \text{h.c. under } \mathcal{G}_{224}, \qquad (20)
\end{aligned}$$

where F, f, h, g are the Majorana couplings and τ is the generator for the SU(2) group.

Within the SO(10) framework, the Yukawa couplings obey the boundary condition $f_{ij} = h_{ij} = g_{ij}$ in the $SU(2)_L \times SU(2)_R \times SU(4)_C \times D$ limit and the same holds true for quartic Higgs couplings $\lambda = \lambda'$ as well. All fermions are right-handed (when the chiral projection on the operator is suppressed) and a fermion field under the high scale Pati–Salam symmetry $\mathcal{G}_{224}$ transforms as

$$\psi_{L,R} = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e \end{pmatrix}_{L,R}. \qquad (21)$$

The diquark Higgs scalars transforming under the SM gauge group $SU(2)_L \times U(1)_Y \times SU(3)_C$ are denoted by the quantum numbers

$$\begin{aligned}
&\Delta_{\nu\nu}(1,0,1),\ \Delta_{u^c u^c}(1,-4/3,6^*),\ \Delta_{d^c d^c}(1,2/3,6^*), \\
&\text{and } \Delta_{u^c d^c}(1,-1/3,6^*). \qquad (22)
\end{aligned}$$

It is clear from Eq. (20) that the Higgs field $\Delta_{\nu\nu}(1,0,1) \subset \Delta_R(1,3,-2,1) \subset (1,3,\overline{10})$ is a neutral complex field. The breaking of $\mathcal{G}_{2113} \to \mathcal{G}_{213}$ is achieved by assigning a VEV to its neutral component $\Delta_{\nu\nu} \subset \Delta_R(1,0,-2,1)$. Its real component acquires a VEV in the ground state which can be represented as $\Delta_{\nu\nu} = v_{B-L} + \frac{1}{\sqrt{2}}(S_r + i\rho)$, while the field ρ gets absorbed by the gauge boson corresponding to the gauge group $U(1)_{B-L}$. Therefore, the remaining real scalar field S_r is indeed the physical Higgs particle which serves our purpose of explaining post-sphaleron baryogenesis and the neutron–antineutron oscillation.

4.2 General expression for CP asymmetry

Without loss of generality, if we consider the particle and antiparticle decay modes of S_r (S_r being its own antiparticle) i.e., $S_r \to u^c d^c u^c d^c d^c d^c$, which gives a change of baryon number $\Delta B_{(S_r\to 6q^c)} = +2$ and $S_r \to \overline{u^c d^c u^c d^c d^c d^c}$, which gives $\Delta B_{(S_r\to 6\overline{q^c})} = -2$, then the CP-asymmetry in baryon number produced by these decays can be quantified as

$$\begin{aligned}
\varepsilon_{CP} &= \frac{\Delta B_{(S_r\to 6q^c)}\,\Gamma(S_r\to 6q^c)}{\Gamma_{\rm tot}} + \frac{\Delta B_{(S_r\to 6\overline{q^c})}\,\Gamma(S_r\to 6\overline{q^c})}{\Gamma_{\rm tot}}, \\
&= \frac{(+2)\,\Gamma(S_r\to 6q^c) + (-2)\,\Gamma(S_r\to 6\overline{q^c})}{\Gamma_{\rm tot}} = 2\,\frac{\Gamma-\bar{\Gamma}}{\Gamma_{\rm tot}},
\end{aligned} \qquad (23)$$

where $\Gamma_{\rm tot} = \Gamma + \bar{\Gamma}$ is the total decay rate with $\Gamma \equiv \Gamma(S_r \to 6q^c)$ and $\bar{\Gamma} \equiv \Gamma(S_r \to 6\overline{q^c})$. It is evident from Eq. (23) that we need divergent partial decay rates for particle and antiparticle decays in order to produce the correct amount of baryon asymmetry and hence we should derive the general conditions under which Γ and $\bar{\Gamma}$ can be different. It is worth to mention here that the other decay modes of S_r have been ignored for simplicity by adjusting the corresponding couplings involved in the respective decay modes.

In generic situations where the theory is CPT-conserving, there can never be a difference between Γ and $\bar{\Gamma}$ if one considers only the tree-level process depicted in Fig. 2, since $\Gamma = \bar{\Gamma}$ at tree level. It is found that the nonzero contribution

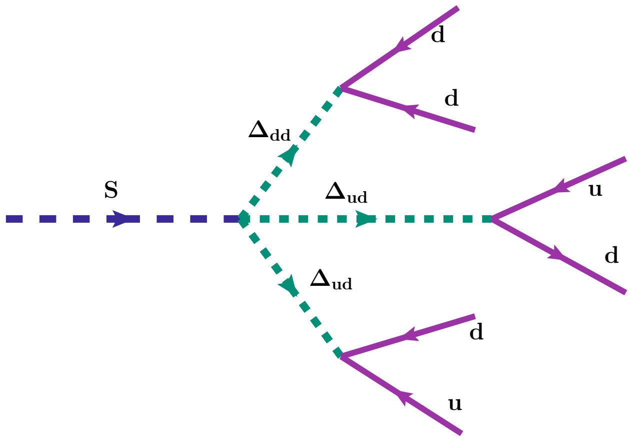


Fig. 2 Feynman diagram representing the decay of $S \to 6q$ at tree level in order to explain post-sphaleron baryogenesis operative at the TeV scale. Since S is a real scalar field, the decay mode $S \to 6\overline{q}$ is possible by reversing the arrow direction of the quark field

to ε_{CP} comes from the interference between the tree-level graph (shown in Fig. 2) and the one-loop corrections (shown in Fig. 3).

4.3 Constraints on post-sphaleron baryogenesis

Here we illustrate how post-sphaleron baryogenesis is slightly different from any other standard baryogenesis process. For post-sphaleron baryogenesis to be successful in explaining the required matter–antimatter asymmetry of our universe, few extra conditions must be satisfied by the model parameters along with the *Sakharov conditions* that say that particle interaction must (i) violate baryon number, B, (ii) violate C and CP, and (iii) be out of thermal equilibrium. Firstly, the S_r Higgs scalar should be lighter than the other members contained in the Pati–Salam multiplet $(1, 3, \overline{10})$ i.e., the diquark Higgs scalars Δ_{qq} so that the baryon number conserving decays involving on-shell Δ_{qq} are kinematically forbidden. Secondly, the out of equilibrium baryon number violating decays should occur after the electroweak phase transition so that it will not be affected by the sphaleron processes which is proactive at >TeV scale. We point out that Ref. [9] neatly elaborates the mechanism of post-sphaleron baryogenesis.

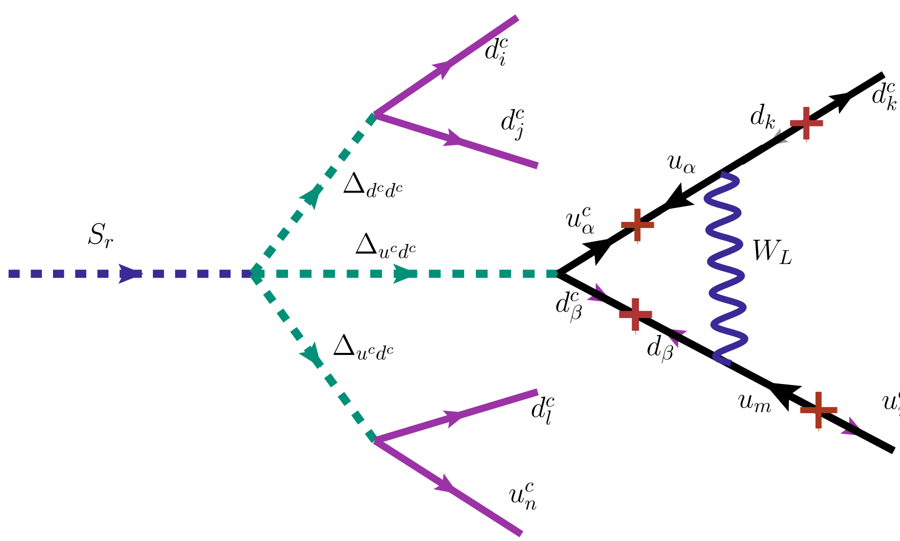
4.4 Out of equilibrium condition

For effectively creating the baryon asymmetry of the universe via post-sphaleron baryogenesis, the decays of $\Gamma(S_r \to 6q^c)$ should satisfy the out of equilibrium condition, which is described by $\Gamma_{S_r} \lesssim H(T)$ where $\Gamma = \Gamma(S_r \to 6q^c) = \frac{36}{(2\pi)^9}\frac{(\mathbf{Tr}[f^\dagger f])^3 \lambda^2 M_S^{13}}{6M_\Delta^{12}}$ is the total decay width and $H \simeq 1.66\sqrt{g_s^*}\,\frac{T^2}{M_{\rm Pl}}$ is the Hubble parameter with the reduced Planck mass $M_{\rm Pl} \simeq 1.2 \times 10^{18}$ GeV and g_s^* is the number of relativistic degrees of freedom. In order to satisfy the out of equilibrium condition, we should have

$$\Gamma_{S_r} \simeq H|_{(T=T_d)}$$
$$\Rightarrow \mathrm{T}_d = \left[\frac{36\,\lambda^2\,\left(\mathbf{Tr}[f^\dagger f]\right)^3\, M_{\rm Pl} M_S^{13}}{(2\pi)^9\, 1.66\, g_*^{1/2} (6M_\Delta)^{12}}\right]^{1/2} \simeq 6.1 \times \left(\frac{M_S^{13}}{M_\Delta^{12}}\right)^{1/2} \mathrm{GeV}^{1/2}. \quad (24)$$

To illustrate the mechanism of post-sphaleron baryogenesis, we require extra fields Δ_{uu}, Δ_{ud}, and Δ_{dd} as color sextets and $SU(2)_L$ singlet scalar bosons that couple to the right-handed quarks contained in the Pati–Salam multiplet $(1, 3, \overline{10})$. For the set of model parameters $M_S = 500$ GeV, $M_\Delta \simeq 1{,}000$ GeV, the decoupling temperature is found to be

Fig. 3 Feynman graphs of the one-loop vertex correction for $\Gamma(S_r \to 6q^c)$



2 GeV, which is well below the EW scale where the sphaleron has been decoupled. Hence, it is inferred from the above equation that the decay of S goes out of equilibrium around $T \simeq M_S$. Below this temperature ($T < M_S$), the decay rate falls very rapidly as the temperature lowers down.

4.5 Estimation of net baryon asymmetry

Now we concentrate on estimating the CP asymmetry coming from the interference term between the tree level and the one-loop level diagrams for the decay of S_r, which is shown in Figs. 2 and 3, respectively. For a discussion of baryon number violation in the loop diagram and the necessary derivation of the interference diagram, interested readers may go through reference [9]. In the present work, we only check whether or not the representative set of model parameters provide the correct number for the required baryon asymmetry of the universe. Hence, without going deep into the derivation, we simply here write the calculated CP asymmetry for post-sphaleron baryogenesis via decay of S_r with baryon number violating interactions:

$$\varepsilon_{\text{wave}} \simeq \frac{g^2}{64\pi \text{Tr}(f^\dagger f)} f_{j\alpha} V^*_{j\beta} f_{i\alpha} \delta_{i3} \frac{m_t m_j}{m_t^2 - m_j^2} \times \sqrt{\left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right)^2 - 4\frac{m_\beta^2}{m_t^2}} \times \left[2\left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right) + \left(1 + \frac{m_\beta^2}{m_t^2}\right) \times \left(\frac{m_t^2}{m_W^2} + \frac{m_\beta^2}{m_t^2} - 1\right) - 4\frac{m_\beta^2}{m_W^2}\right], \tag{25}$$

$$\varepsilon_{\text{vertex}} \simeq \frac{g^2}{32\pi \text{Tr}(f^\dagger f)} f_{i\beta} V^*_{i\beta} f_{i\alpha} \delta_{i3} \frac{m_j m_\beta}{m_W^2} \times \left[1 + \frac{9m_W^2}{M_S^2} \ln\left(1 + \frac{M_S^2}{3m_W^2}\right)\right], \tag{26}$$

$$\varepsilon_{\text{CP}} = \varepsilon_{\text{wave}} + \varepsilon_{\text{vertex}}. \tag{27}$$

Here the expression in Eq. (25) represents the CP asymmetry coming from interference between the tree and one-loop self energy diagram while the expression in Eq. (26) represents the CP asymmetry due to interference of the tree and one-loop vertex diagram (see Ref. [9] for details). In the above expression, V is the well-known CKM matrix in the quark sector, i, j correspond to the up-quark indices u, c, t, while α, β represent down-quark indices d, s, b. A sum over repeated indices (Einstein convention) is assumed here. The δ_{i3} is due to the fact that the CP asymmetry is nonzero only when we have a top quark in the final state (since only the CKM elements involving the third generation have a large imaginary part).

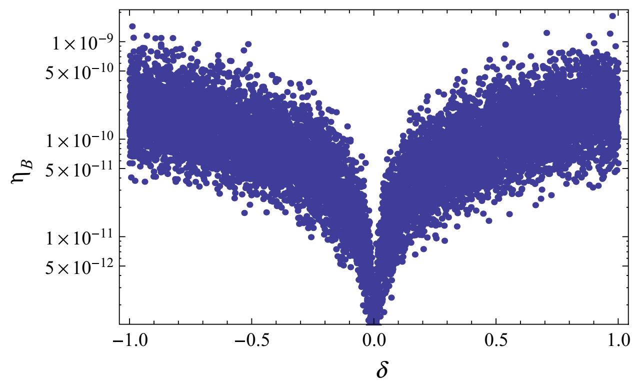


Fig. 4 Estimation of final baryon asymmetry in terms of CP asymmetry with overall phase δ contained in the CKM mixing matrix

As mentioned earlier, the mechanism of post-sphaleron baryogenesis provides a natural explanation for the observed baryon asymmetry of our universe i.e., $\eta_B \simeq 10^{-10}$. Using $m_c = 1.27$ GeV, $m_b = 4.25$ GeV, $m_t = 172$ GeV, the CKM mixing elements V_{CKM}, and the Yukawa couplings relevant for color scalar particles in their allowed range, the CP asymmetry via the decay of S_r through loop diagrams with the exchanges of $W^\pm$ bosons is estimated to be 10^{-8}. A further dilution of the baryon asymmetry arises from the fact that $T_d \ll M_S$, since the decay of S_r releases entropy into the universe. As a result the final baryon asymmetry, taking into account the dilution factor, becomes

$$\eta_B = \varepsilon_{\text{CP}} \times \left(\frac{T_d}{M_S}\right), \tag{28}$$

where T_d is the decoupling temperature of the color scalar and M_S is the mass of the scalar. The condition $T_d/M_S \geq 10^{-2}$ otherwise leads to suppressed baryon asymmetry, which finally results in a baryon asymmetry in the range of 10^{-10}. The scatter plot between the final baryon asymmetry including dilution factor (η_B) with this phase (δ_{i3}) is shown in Fig. 4.

5 Observable neutron–antineutron oscillation with TeV scale diquark Higgs scalars

5.1 Feynman amplitudes for neutron–antineutron oscillation

We consider the contributions arising only from the RH diquark Higgs fields having masses at the TeV scale while ignoring the contributions from LH diquark Higgs fields, since they have masses around the eV range. The Feynman diagrams contributing to the neutron–antineutron oscillation are shown in Fig. 5 (loop diagram), Fig. 6a and b. Our prime goal is to estimate the mixing time for this loop diagram, clarifying why we have suppressed other contributions within our model parameters.

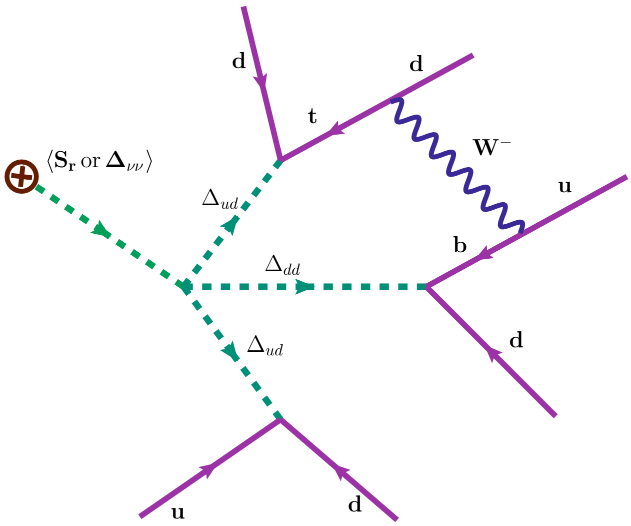


Fig. 5 Loop contributions to neutron–antineutron oscillation in the post-sphaleron baryogenesis operative at the TeV scale

There are two types of contributions to the n–$\bar{n}$ oscillation in the right-handed sector at loop level, (i) one involving one $u^c u^c$-type and two $d^c d^c$-type, (ii) another one involving one $d^c d^c$-type and two $u^c d^c$-type Δ-bosons. The Feynman amplitude for the second type of contribution where one needs to change the two b^c quarks to two d^c quarks from the already generated effective operator $u^c d^c b^c u^c d^c b^c$ via a second order weak interactions (given in Fig. 5) can be written

$$\mathcal{A}^{1-\text{loop}}_{n-\bar{n}} \simeq \frac{(f_{ud})_{11}(f_{ud})_{13}(f_{dd})_{13}\,\lambda v_{B-L}}{M^4_{u^c d^c} M^2_{d^c d^c}} \frac{g^4\, V^2_{td}\, m^2_b\, m^2_t}{(16\pi^2)^2 M^4_{W_L}} \times \log\left(\frac{m^2_b}{M^2_{W_L}}\right). \tag{29}$$

The Feynman amplitude for tree-level processes shown in Fig. 6a and b (which are suppressed with the choice of our model parameters) can be written

$$\mathcal{A}^{\text{tree}}_{n-\bar{n}} = \mathcal{A}^{(a)}_{n-\bar{n}} + \mathcal{A}^{(b)}_{n-\bar{n}} \simeq \frac{(f_{dd})_{11}(f_{ud})^2_{11}\,\lambda\, v_{B-L}}{M^4_{u^c d^c} M^2_{d^c d^c}} + \frac{(f_{uu})_{11}(f_{dd})^2_{11}\,\lambda\, v_{B-L}}{M^4_{d^c d^c} M^2_{u^c u^c}}. \tag{30}$$

5.2 Prediction for neutron–antineutron mixing time $\tau_{n-\bar{n}}$

Before estimating the n–$\bar{n}$ oscillation mixing time one should carefully fix the input parameters in order to satisfy flavor changing neutral current (FCNC) constraints and to give correct amount of baryon asymmetry of the universe. For example, using a diquark sextet Higgs scalar mass around TeV scale, the corresponding Yukawa coupling $(f_{dd})_{11} \simeq 0.001$–$0.1$ along with the other allowed range of model parameters contradicts the FCNC constraints and hampers post-sphaleron baryogenesis even though it predicts a neutron–antineutron oscillation time (as shown in Fig. 6) within the experimental search limits. So this means that one has to choose the Majorana Yukawa coupling f accordingly. Now we briefly discuss how this choice of f can be achieved within the framework of SO(10) (elaborated in Ref. [19]).

It is found in Ref. [19] that all charged fermion masses and CKM mixing can be fitted well at the GUT scale within the framework of SO(10) with two kinds of structures; I) with a single Higgs representation 126_H, II) with two Higgs representations 126_H, $126'_H$. As has been derived, structure I with Yukawa coupling $f_{126_H} = \text{diag}(0.0236, -0.38, 1.5)$ estimates n–$\bar{n}$ oscillation mixing time to be 10^9 s, which does not serve our purpose. Rather we consider structure II where the dominant contribution to the n–$\bar{n}$ oscillation comes from the loop diagram while suppressing the tree-level contribution. This choice of having two Higgs bosons, 126_H, $126'_H$, not only fits the fermion masses at the GUT scale, but it also allows the RH neutrino Majorana mass and hence the corresponding Yukawa coupling $f_{126'_H}$ as per our requirement. Due to the second Higgs representation $126'$ with its Yukawa

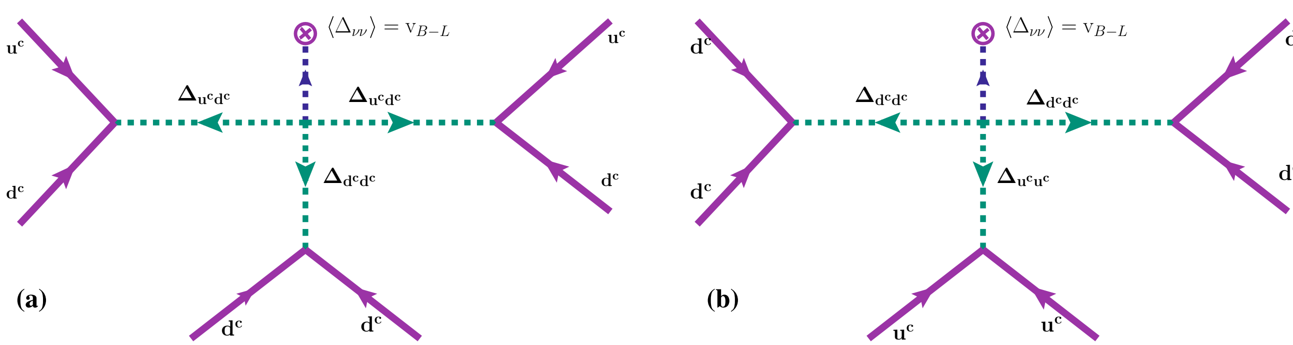


Fig. 6 Feynman diagrams contributing to neutron–antineutron oscillation. The figure in the *left-panel* involves two $\Delta_{u^c d^c}$ and one $\Delta_{d^c d^c}$ bosons whereas the figure in the *right panel* involves two $\Delta_{d^c d^c}$ and one $\Delta_{u^c u^c}$ bosons. The structure of the theory is such that these tree-level contributions are suppressed in the present work

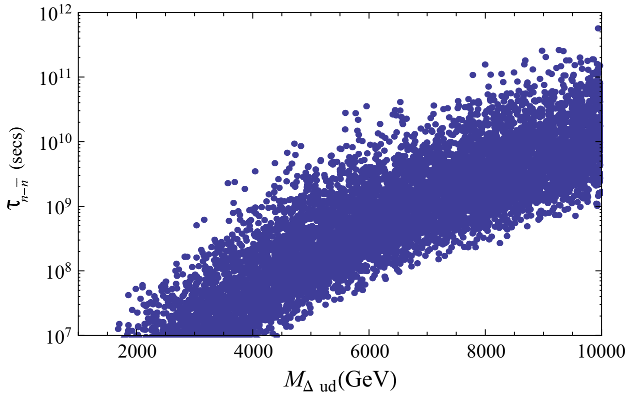


Fig. 7 Estimation of $\tau_{n-\bar{n}}$ as a function of diquarks mass $M_{\Delta_{ud}}$

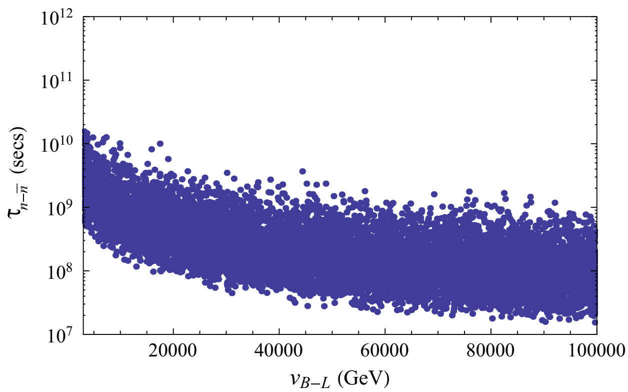


Fig. 8 Estimation of $\tau_{n-\bar{n}}$ as a function of $B-L$ breaking scale v_{B-L}, while keeping the other model parameters within their allowed range, consistent with the mechanism of post-sphaleron baryogenesis

coupling f' to fermions we get $v_{\xi'} = 1$–100 MeV following the same procedure, provided all other components are at the GUT scale except $\xi'(2, 2, 15)$, which is at the intermediate scale $M_{\xi'} = 10^{13}$–10^{14} GeV. By treating the mass of $\xi(2, 2, 15) \subset 126$ to remain at its natural GUT-scale value, its induced VEV is negligible and precision unification with large GUT-scale value is unaffected except for phenomenologically inconsequential additional threshold effects. Then defining $F = f' v_{\xi'}$ gives exactly the same fit to the GUT-scale fermion masses and mixings but now with the diagonal structure $f'_i = (0.0236, -0.38, 1.5)$. But since $< \Delta'_R >= 0$ and only $\Delta_R \subset 126_H$ with VEV v_R is used to break G_{2113}, the coupling f and hence M_N are allowed to have any 3×3 form without any restriction. In order to suppress the tree-level contributions to the n–$\bar{n}$ oscillation as shown in Fig. 6 which otherwise causes problems in baryon asymmetry, we particularly choose the Majorana coupling f_{dd} as per our requirement, i.e., $f_{dd\,11} \leq 10^{-5}$.

Using this particular choice of Yukawa couplings i.e., $f_{dd\,11}, f_{dd\,22}, \leq 10^{-5}$, and others in the range of 0.001–1.0, one can calculate the mixing time for neutron–antineutron oscillation as a function of the mass of the color Higgs scalar ($B-L$ breaking scale) as shown in Fig. 7 (Fig. 8).

Table 2 Numerical estimation of neutrino–antineutrino oscillation time

f_{13}	g_{11}	g_{13}	λ	$M_{\Delta ud}$ (GeV)	$M_{\Delta dd}$ (GeV)	$\tau_{n-\bar{n}}$ (s)
0.001	0.01	0.01	0.1	10^3	10^4	3.96×10^8
0.001	0.01	0.01	0.1	10^3	10^5	8.72×10^{10}
0.001	0.01	0.01	1	10^3	10^5	3.29×10^9
0.001	0.001	0.001	0.1	10^3	10^4	4.42×10^{10}

The n–$\bar{n}$ amplitude can be translated into the n–$\bar{n}$ oscillation time:

$$\tau^{-1}_{n-\bar{n}} = \delta m_{n-\bar{n}} = C_{\rm QCD}(\mu_\Delta, 1\,\text{GeV})|A^{1-\text{loop}}_{n-\bar{n}}| \tag{31}$$

with $C_{\rm QCD}(\mu_\Delta, 1\,\text{GeV}) = 0.1\text{GeV}^6$ as used in Ref. [9]. The estimated n–$\bar{n}$ oscillation time for various choices of model parameters i.e., $f_{ud\,11} \leq 10^{-5}$, $M_S = (100 - 5{,}000) GeV$, $B-L$ breaking scale from (3–5) TeV and the masses of $M_{\Delta ud/dd}$ between M_S and V_{B-L}, $\lambda \simeq 0.01$–1.0 is presented in Table 2.

5.3 Coupling unification including diquarks at the TeV scale

It is evident that the post-sphaleron baryogenesis and neutron–antineutron oscillation phenomena require the existence of color Higgs scalars, having masses around TeV scale. In this subsection, we intend to examine whether unification of the gauge couplings is still possible after the addition of extra color scalars Δ_{ud}, Δ_{dd}, Δ_{uu} to the existing particle content as noted in Sect. 3, by studying their respective renormalization group equations. The one-loop beta coefficients derived for the present model along with their gauge symmetry groups, range of mass scales, and spectrum of Higgs scalars necessary for gauge coupling unification to explain the TeV scale post-sphaleron baryogenesis and neutron–antineutron oscillation are given by

(i) $\mu = \mathbf{M_Z}(\mathbf{91.817}\,\text{GeV}) - \mathbf{M_T}(\mathbf{1}\,\text{TeV})$:
$\mathcal{G} = \mathcal{G}_{2_L 1_Y 3_C} \equiv \text{SM}$
Higgs: $\Phi(2, 1/2, 1)_{10}$: $\boldsymbol{a_i} = (-19/6,\ 41/10,\ -7)$; (32)

(ii) $\mu = \mathbf{M_T}(\mathbf{1}\,\text{TeV}) - \mathbf{M_{B-L}}(\mathbf{3}\,\text{TeV})$: $\mathcal{G} = \mathcal{G}_{2_L 1_Y 3_C}$,
Higgs: $\Phi(2, 1/2, 1)_{10} \oplus S(1, 0, 1)_{126} \subset \Delta_R$
$\oplus \Delta_{u^c d^c}(1, -1/3, 6^*)_{126} \oplus \Delta_{d^c d^c}(1, 2/3, 6^*)_{126}$
$\oplus \Delta_{u^c u^c}(1, -4/3, 6^*)_{126}$:
$\boldsymbol{a_i} = (-19/6,\ 207/30,\ -27/6)$, (33)

(iii) $\mu = \mathbf{M_{B-L}}(\mathbf{3}\,\text{TeV}) - \mathbf{M_\Omega}(\mathbf{10}\,\text{TeV})$: $\mathcal{G} = \mathcal{G}_{2_L 1_R 1_{B-L} 3_C}$,
Higgs: $\Phi_1(2, 1/2, 0, 1)_{10} \oplus \Phi_2(2, -1/2, 0, 1)_{10'}$
$\oplus \Delta_R(1, 1, -1, 1)_{126} \oplus \chi_R(1, 1/2, -1/2, 1)_{16}$,

$$\oplus\Delta_{u^c d^c}(1, 1, -2/3, 6^*)_{126}$$
$$\oplus\Delta_{d^c d^c}(1, 0, -2/3, 6^*)_{126}$$
$$\oplus\Delta_{u^c u^c}(1, 0, -2/3, 6^*)_{126} :$$
$$\boldsymbol{a_i} = (-3,\ 35/4,\ 45/8,\ -27/6), \tag{34}$$

(iv) $\mu = \mathbf{M}_\Omega(10^4\,\text{GeV}) - \mathbf{M_C}(\mathbf{10^5} - \mathbf{10^6}\,\text{GeV})$:
$$\mathcal{G} = \mathcal{G}_{2_L 2_R 1_{B-L} 3_C},$$
$$\text{Higgs: } \Phi_1(2, 2, 0, 1)_{10} \oplus \Phi_2(2, 2, 0, 1)_{10'}$$
$$\oplus\Delta_R(1, 3, -1, 1)_{126} \oplus \chi_R(1, 2, -1/2, 1)_{16},$$
$$\oplus\Delta_{u^c d^c}(1, 3, -2/3, 6^*)_{126}$$
$$\oplus\Delta_{d^c d^c}(1, 3, -2/3, 6^*)_{126}$$
$$\oplus\Delta_{u^c u^c}(1, 3, -2/3, 6^*)_{126} \oplus \Omega_R(1, 3, 0, 1)_{210}$$
$$\boldsymbol{a_i} = (-8/3,\ 4/3,\ 55/4,\ -2). \tag{35}$$

In analogy to the above discussion, we have two scenarios; one without bitriplet and another with bitriplet Higgs scalar (3, 3, 1) under the Pati–Salam group $SU(2)_L \times SU(2)_R \times SU(4)_C$, while its effect has been included from M_C onwards to the unification scale M_U. Accordingly, we have estimated the one-loop beta coefficients for these two scenarios:

(v) $\mu = \mathbf{M_C} - \mathbf{M}_\xi$: $\mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$,
$$\text{Higgs: } \Phi_1(2, 2, 1)_{10} \oplus \Phi_2(2, 2, 1)_{10'} \oplus \Delta_R(1, 3, \overline{10})_{126}$$
$$\oplus\chi_R(1, 2, \bar{4})_{16} \oplus \Omega_R(1, 3, 15)_{210},$$
$$\boldsymbol{a_i} = (-8/3,\ 29/3,\ -14/3), \tag{36}$$

(vi) $\mu = \mathbf{M}_\xi - \mathbf{M_P}$: $\mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$,
$$\text{Higgs: } \Phi_1(2, 2, 1)_{10},\ \Phi_2(2, 2, 1)_{10'},\ \Delta_R(1, 3, \overline{10})_{126},$$
$$\chi_R(1, 2, \bar{4})_{16},\ \Omega_R(1, 3, 15)_{210} + \xi(2, 2, 15)_{126'},$$
$$\boldsymbol{a_i} = (7/3,\ 44/3,\ 2/3), \tag{37}$$

(vii) $\mu = \mathbf{M_P} - \mathbf{M_U}$: $\mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$,
$$\text{Higgs: } \Phi_1(2, 2, 1)_{10},\ \Phi_2(2, 2, 1)_{10'},\ \Delta_R(1, 3, \overline{10})_{126},$$
$$\Delta_L(3, 1, 10)_{126},\ \chi_R(1, 2, \bar{4})_{16},\ \chi_L(1, 2, 4)_{16},$$
$$\Omega_R(1, 3, 15)_{210},\ \Omega_L(3, 1, 15)_{210},\ \xi(2, 2, 15)_{126'},$$
$$\Sigma'(1, 1, 15)_{210},$$
$$\boldsymbol{a_i} = (44/3,\ 44/3,\ 6). \tag{38}$$

The gauge coupling unification after the addition of extra color sextet scalars particles is shown in Fig. 9 with the allowed mass scales desirable for our model predictions,

$$M_{B-L} = 4 - 7\ \text{TeV},\ M_\Omega = 10\ \text{TeV},\ M_C = 10^5 - 10^6\ \text{GeV},$$
$$M_P \simeq 10^{14.65}\ \text{GeV and } M_U \simeq 10^{16.25}\ \text{GeV}. \tag{39}$$

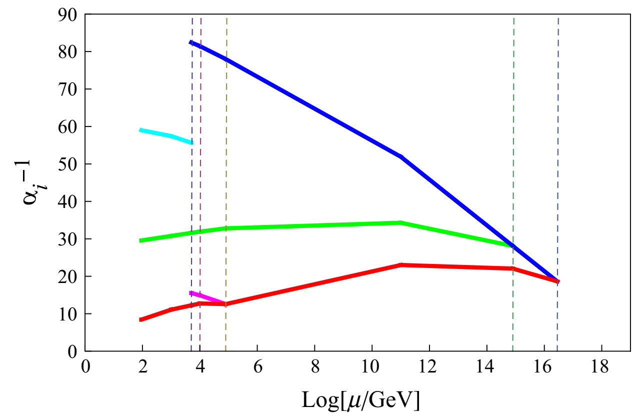


Fig. 9 Coupling unification for the present model where $\Delta_{u^c d^c}$, $\Delta_{d^c d^c}$, and $\Delta_{u^c u^c}$ have been included at the TeV scale keeping in mind that these particle mediate neutron–antineutron oscillation and baryon asymmetry and including $\xi(2, 2, 15)$ around 10^{12} GeV in order to fit the fermions masses at the GUT scale

6 Viability of the model

As already known, the lepton flavor and lepton number violating dilepton signals can be probed from the production of heavy RH Majorana neutrinos via $p+p \to W_R^\pm \to \ell_\alpha^\pm + N_R$, from which N_R may further decay into $N_R \to W_R^* \to \ell_\beta^\mp = 2j$. This process, being the main channel for N_R production via on-shell Z_R production and W_R fusion, needs to be verified at LHC and our model suits the purpose, since we have W_R, Z_R gauge bosons and scalar diquarks at the TeV scale. A more pleasant situation is that the model, though non-supersymmetric, predicts similar branching ratios as in supersymmetric models for LFV processes like $\mu \to e\gamma$, $\tau \to \mu\gamma$, and $\tau \to e\gamma$. The predicted branching ratios for these LFV decays, being closer to the current experimental search limits can be used to verify the left–right framework in this model. Moreover, the estimated neutron–antineutron oscillation mixing time, gauge coupling unification and proton life time in the model stay in the range of ongoing search experiments.

Besides all these points, the model can also predict a number of verifiable new physical quantities like (i) a new non-standard contribution to $0\nu2\beta$ rate in the W_L–W_L channel, (ii) contributions to branching ratios of lepton flavor violating (LFV) decays, (iii) leptonic CP-violation due to non-unitarity effects, and (iv) experimentally verifiable proton decay modes such as $p \to e^+\pi^0$, provided the gauged inverse seesaw mechanism is found to be operative. We find it appropriate to mention here that these physical quantities were also discussed in a recent work [19], but in that model the asymmetric left–right gauge symmetry was incorporated at $\simeq$ 10 TeV.

7 Conclusion

We have closely studied the mechanism of post-sphaleron baryogenesis, which can potentially explain the matter–antimatter asymmetry of the present universe, by analyzing the basic interactions using quarks and diquark Higgs scalars under high scale Pati–Salam symmetry and low scale SM-like interactions at the TeV scale. The study estimates the total baryon asymmetry to be $\eta_B \simeq \mathcal{O}(10^{-10})$ and neutron–antineutron oscillation with mixing time to be $\tau_{n-\bar{n}} \simeq \mathcal{O}(10^{-10}\text{–}10^{-8})$ s, which may be accessible at ongoing search experiments. We have made a humble attempt to embed the framework of PSB in a non-SUSY SO(10) model with Pati–Salam symmetry as a low scale intermediate breaking step where we have shown a strong interlink between post-sphaleron baryogenesis and neutron–antineutron oscillation operative at the TeV scale and we laid out a novel mechanism of inducing the required CP asymmetry via the SM $W_L^\pm$ loops.

More essentially, we have embedded the TeV scale LR model within the framework of the SO(10) model, where the predicted mass for light neutrinos matches with the neutrino oscillation data. Our calculations indicate that the TeV scale masses of $W_R^\pm$ and heavy RH neutrinos can also give dominant non-standard contributions to neutrinoless double beta decay, which may sound crucial to the experimentalists. Some more good features of the model are an explanation of the nonzero light neutrino masses via the extended/inverse seesaw mechanism, a new non-standard contribution to neutrinoless double beta decay, and leptonic CP-violation from non-unitary effects.

Acknowledgments Sudhanwa Patra would like to thank the organizers of the workshop entitled "Majorana to LHC: Origin of neutrino Mass" at ICTP, Trieste, Italy during 2–5 October, 2013 where the idea for this work was conceived. Both the authors sincerely acknowledge P.S. Bhupal Dev for his useful clarification while preparing the manuscript. Prativa Pritimita is grateful to the Department of Science and Technology, Govt. of India for INSPIRE Fellowship (IF140299). The work of Sudhanwa Patra is supported by the Department of Science and Technology, Govt. of India under the financial Grant SERB/F/482/2014-15.

References

1. J. Dunkley et al., WMAP Collaboration. arXiv:0803.0586 [astro-ph]
2. E. Komatsu et al., Seven-year wilkinson microwave anisotropy probe (WMAP) observations: cosmological interpretation. Astrophys. J. Suppl. **192**, 18 (2011). doi:10.1088/0067-0049/192/2/18. arXiv:1001.4538 [astro-ph]
3. W.-M. Yao et al., Particle data group: 2006, partial update for edition 2008. J. Phys. G **33**, 1 (2006). http://pdg.lbl.gov
4. M. Fukugita, T. Yanagida, Baryogenesis without grand unification. Phys. Lett. B **174**, 45 (1986)
5. D.E. Morrissey, M.J. Ramsey-Musolf, Electroweak baryogenesis. New J. Phys. **14**, 125003 (2012)
6. W. Buchmuller, R.D. Peccei, T. Yanagida, Leptogenesis as the origin of matter. Annu. Rev. Nucl. Part. Sci. **55**, 311–355 (2005). doi:10.1146/annurev.nucl.55.090704.151558. arXiv:0502169 [hep-ph]
7. S. Davidson, E. Nardi, Y. Nir, Leptogenesis. Phys. Rep. **466**, 105–177 (2008). doi:10.1016/j.physrep.2008.06.002. arXiv:0802.2962 [hep-ph]
8. K.S. Babu, R.N. Mohapatra, Coupling unification, GUT-scale baryogenesis and neutron-antineutron oscillation in SO(10). Phys. Lett. B **715**, 328–334 (2012). doi:10.1016/j.physletb.2012.08.006. arXiv:1206.5701 [hep-ph]
9. K.S. Babu, P.S. Bhupal Dev, E.C.F.S. Fortes, R.N. Mohapatra, Post-sphaleron baryogenesis and an upper limit on the neutron–antineutron oscillation time. Phys. Rev. D **87**, 115019 (2013). doi:10.1103/PhysRevD.87.115019. arXiv:1303.6918 [hep-ph]
10. K.S. Babu, R.N. Mohapatra, S. Nasri, Post-sphaleron baryogenesis. Phys. Rev. Lett. **97**, 131301 (2006). doi:10.1103/PhysRevLett.97.131301. arXiv:0606144 [hep-ph]
11. R. Mohapatra, J.C. Pati, A natural left-right symmetry. Phys. Rev. D **11**, 2558 (1975). doi:10.1103/PhysRevD.11.2558
12. J.C. Pati, A. Salam, Lepton number as the fourth color. Phys. Rev. D **10**, 275 (1974). doi:10.1103/PhysRevD.10.275
13. G. Senjanovic, R.N. Mohapatra, Exact left–right symmetry and spontaneous violation of parity. Phys. Rev. D **12**, 1502 (1975). doi:10.1103/PhysRevD.12.1502
14. R.N. Mohapatra, G. Senjanovic, Neutrino masses and mixings in gauge models with spontaneous parity violation. Phys. Rev. D **23**, 165 (1981). doi:10.1103/PhysRevD.23.165
15. R.N. Mohapatra, G. Senjanovic, Neutrino mass and spontaneous parity violation. Phys. Rev. Lett. **44**, 912 (1980). doi:10.1103/PhysRevLett.44.912
16. N. Deshpande, J. Gunion, B. Kayser, F.I. Olness, Left–right symmetric electroweak models with triplet Higgs. Phys. Rev. D **44**, 837–858 (1991). doi:10.1103/PhysRevD.44.837
17. G. Lazarides, Q. Shafi, C. Wetterich, Proton lifetime and fermion masses in an SO(10) model. Nucl. Phys. B **181**, 287 (1981). doi:10.1016/0550-3213(81)90354-0
18. P.S. Bhupal Dev, C.-H. Lee, R.N. Mohapatra, Natural TeV-scale left–right seesaw for neutrinos and experimental tests. arXiv:1309.0774 [hep-ph]
19. R.L. Awasthi, M. Parida, S. Patra, Neutrino masses, dominant neutrinoless double beta decay, and observable lepton flavor violation in left–right models and SO(10) grand unification with low mass W_R, Z_R bosons. JHEP **08**, 122 (2013). doi:10.1007/JHEP08(2013)122. arXiv:1302.0672 [hep-ph]
20. P. Minkowski, Phys. Lett. **B67**, 421 (1977)
21. M. Gell-Mann, P. Ramond, R. Slansky (1980), print-80-0576 (CERN)
22. T. Yanagida, in Proceedings of the Workshop on the Baryon Number of the Universe and Unified Theories, Tsukuba, Japan, 13–14 Feb 1979
23. R.N. Mohapatra, G. Senjanovic, Phys. Rev. Lett **44**, 912 (1980)
24. J. Schechter, J.W.F. Valle, Phys. Rev. D **22**, 2227 (1980)
25. R.N. Mohapatra, Phys. Rev. Lett. **56**, 561 (1986)
26. R.N. Mohapatra, J.W.F. Valle, Phys. Rev. D **34**, 1642 (1986)
27. P.S.B. Dev, R.N. Mohapatra, Phys. Rev. D **81**, 013001 (2010). arXiv:0910.3924 [hep-ph]
28. K. Nakamura et al., Particle data group. J. Phys. G **37**, 075021 (2010)
29. C. Amsler et al., Particle data group. Phys. Lett. B **667**, 1 (2008)
30. ATLAS Collaboration, G. Aad et al., Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. Eur. Phys. J. C **72**, 2056 (2012). doi:10.1140/epjc/s10052-012-2056-4. arXiv:1203.5420 [hep-ex]
31. CMS Collaboration, S. Chatrchyan et al., Search for heavy neutrinos and W[R] bosons with right-handed couplings in a left–right

symmetric model in pp collisions at sqrt(s) = 7 TeV. Phys. Rev. Lett. **109**, 261802 (2012). doi:10.1103/PhysRevLett.109.261802. arXiv:1210.2402 [hep-ex]
32. K.S. Babu, R.N. Mohapatra, Predictive neutrino spectrum in minimal SO(10) grand unification. Phys. Rev. Lett. **70**, 2845 (1993). doi:10.1103/PhysRevLett.70.2845. arXiv:9209215 [hep-ph]
33. S. Bertolini, L. Di Luzio, M. Malinsky, Light color octet scalars in the minimal SO(10) grand unification. Phys. Rev. D **87**, 085020 (2013). arXiv:1302.3401 [hep-ph]
34. L.E. Ibanez, C. Munoz, Enhancement factors for supersymmetric proton decay in the Wess–Zumino gauge. Nucl. Phys. B **245**, 425 (1984). doi:10.1016/0550-3213(84)90439-5
35. A.J. Buras, J.R. Ellis, M.K. Gaillard, D.V. Nanopoulos, Aspects of the grand unification of strong, weak and electromagnetic interactions. Nucl. Phys. B **135**, 66–92 (1978). doi:10.1016/0550-3213(78)90214-6
36. P.S. Bhupal Dev, R.N. Mohapatra, Electroweak symmetry breaking and proton decay in SO(10) SUSY-GUT with TeV W_R. Phys. Rev. D **82**, 035014 (2010). doi:10.1103/PhysRevD.82.035014. arXiv:1003.6102 [hep-ph]
37. Super-Kamiokande Collaboration, H. Nishino et al., Search for nucleon decay into charged anti-lepton plus meson in Super-Kamiokande I and II. Phys. Rev. D **85**, 112001 (2012). doi:10.1103/PhysRevD.85.112001. arXiv:1203.4030 [hep-ph]
38. K.S. Babu et al., Proton decay, presented at the workshop on fundamental physics at the intensity frontier, Rockville, Maryland, Nov. 20–Dec. 2 (2011). arXiv:1205.2671 [hep-ex]
39. K. Abe et al., Letter of intent: the Hyper-Kamiokande experiment—detector design and physics potential (2011). arXiv:1109.3262 [hep-ex]