Spontaneous parity breaking, gauge coupling unification, and consistent cosmology with transitory domain walls

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The formation of transitory domain walls is quite generic in theories with spontaneous breaking of discrete symmetries. Since these walls are in conflict with cosmology, there has to be some mechanism which makes them disappear. We study one such mechanism by incorporating Planck-scale suppressed operators within the framework of left-right symmetric models where left-right parity (D parity) is spontaneously broken. We find that this mechanism cannot make the walls disappear in minimal versions of left-right symmetric models. We propose two viable extensions of this model and show that Planck-scale suppressed operators can give rise to the successful disappearance of domain walls provided the scale of parity breaking obeys certain limits. We also constrain the scale of parity breaking by demanding successful gauge-coupling unification and make a comparison of the unification and cosmology bounds.

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I. INTRODUCTION

Spontaneous parity breaking can be naturally explained within the framework of left-right symmetric models (LRSM) [1] which have been considered a novel extension of the standard model and studied extensively for last few decades. Also, tiny neutrino masses [2] can be successfully implemented via the seesaw mechanism [3,4] without reference to very high-scale physics such as grand unification. Incorporating supersymmetry into such models has several other motivations like protecting the scalar sector from quadratic divergences, providing a natural dark matter candidate among others. However, as studied previously in Refs. [5,6], generic Supersymmetric Left-Right models are tightly constrained from consistent cosmology as well as the successful gauge-coupling unification point of view and in quite a few cases these models do not give rise to successful unification and consistent cosmology simultaneously. With a view of this, we intend to study nonsupersymmetric versions of LRSM and check if both of these constraints can be satisfied simultaneously.

Spontaneous breaking of exact discrete symmetries like parity (which we shall denote as D-parity hereafter) has cosmological implications since they lead to frustrated phase transitions leaving behind a network of domain walls (DW). These domain walls, if not removed will be in conflict with the observed Universe [7,8]. It was pointed out [9,10] that Planck-scale suppressed nonrenormalizable operators can be a source of domain wall instability. Gauge structure of the underlying theory dictates the structure of these nonrenormalizable operators. In the presence of supersymmetry, the constraints on the D-parity breaking scale was discussed in Ref. [5]. Here we perform the same analysis in the absence of supersymmetry and also check if successful gauge-coupling unification can be achieved simultaneously in these models. Earlier studies on gauge-coupling unification in nonsupersymmetric LRSM were done in Refs. [11,12] and very recently in Ref. [13]. Here we adopt the procedure outlined in Ref. [12] for gauge-coupling unification and that in Ref. [5] for the domain-wall disappearance mechanism to show that in the minimal versions of nonsupersymmetric LRSM, successful gauge-coupling unification and domain-wall disappearance can not be achieved simultaneously. We then propose two possible extensions of such minimal models which can successfully give rise to both of these desired outcomes.

It is worth mentioning that the formation of domain walls is not generic in all Left-Right models. Models where D-parity and $SU(2)_R$ gauge symmetry are broken at two different stages do not suffer from this problem [14]. In these models, the vacuum expectation value (vev) of a parity-odd singlet field breaks the D-parity first and $SU(2)_R$ gauge symmetry gets broken at a later stage by either Higgs triplets or Higgs doublets.

This paper is organized as follows. In Sec. II we briefly review the domain wall dynamics. In Sec. III we discuss minimal LRSM with Higgs doublets and with Higgs triplets, and discuss how the requirement of the successful disappearance of domain walls gives rise to unphysical constraints on the parity breaking scale. In Sec. IV we discuss two viable extensions of the minimal LRSM which can provide a viable solution to the domain wall problem. Then in Sec. V, we study gauge-coupling unification in both minimal and extended LRSM and finally summarize our results in Sec. VI.

II. DOMAIN WALL DYNAMICS

Discrete symmetries and their spontaneous breaking are both common instances and desirable in particle physics model building. The spontaneous breaking of such discrete symmetries gives rise to a network of domain walls leaving

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the accompanying phase transition frustrated [7,8]. The danger of a frustrated phase transition can therefore be evaded if a small explicit breaking of discrete symmetry can be introduced.

If the amount of such discrete symmetry breaking is small, the resulting domain walls may be relatively long-lived and can dominate the Universe for a sufficiently long time. However, this will be in conflict with the observed Universe and hence these domain walls need to disappear at a very high energy scale (at least before Big Bang Nucleosynthesis). In view of this, we summarize the three cases of domain wall dynamics discussed in Ref. [5], one of which originates in the radiation-dominated (RD) Universe and destabilized also within the RD Universe. This scenario was originally proposed by Kibble [7] and Vilenkin [15]. The second scenario was essentially proposed in Ref. [16], which consists of the walls originating in a RD phase, subsequent to which the Universe enters a matter-dominated (MD) phase, either due to substantial production of heavy unwanted relics such as moduli, or simply due to a coherent oscillating scalar field. The third one is a variant of the MD model in which the domain walls dominate the Universe for a considerable epoch giving rise to a mild inflationary behavior or weak inflation (WI) [17,18]. In all these cases the domain walls disappear before they come to dominate the energy density of the Universe.

When a scalar field ϕ acquires a vev at a scale M_R at some critical temperature T_c, a phase transition occurs leading to the formation of domain walls. The energy density trapped per unit area of such a wall is $\sigma \sim M_R^3$. The dynamics of the walls are determined by two quantities, force due to tension $f_T \sim \sigma/R$ and force due to friction $f_F \sim \beta T^4$, where R is the average scale of radius of curvature prevailing in the wall complex, β is the speed at which the domain wall is navigating through the medium and T is the temperature. The epoch at which these two forces balance each other sets the time scale $t_R \sim R/\beta$. Putting all these together leads to the scaling law for the growth of the scale $R(t)$:

$$R(t) \approx (G\sigma)^{1/2} t^{3/2}. \tag{1}$$

The energy density of the domain walls goes as $\rho_W \sim (\sigma R^2/R^3) \sim (\sigma/Gt^3)^{1/2}$. In a RD era this ρ_W is comparable to the energy density of the Universe $[\rho \sim 1/(Gt^2)]$ around time $t_0 \sim 1/(G\sigma)$.

The pressure difference arising from small asymmetry on the two sides of the wall competes with the two forces $f_F \sim 1/(Gt^2)$ and $f_T \sim (\sigma/(Gt^3))^{1/2}$ discussed above. For $\delta\rho$ to exceed either of these two quantities before $t_0 \sim 1/(G\sigma)$

$$\delta\rho \geq G\sigma^2 \approx \frac{M_R^6}{M_{\rm Pl}^2} \sim M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^2. \tag{2}$$

Similar analysis in the MD era, originally considered in Ref. [16] begins with the assumption that the initially formed wall complex in a phase transition is expected to rapidly relax to a few walls per horizon volume at an epoch characterized by Hubble parameter value H_i. Thus the initial energy density of the wall complex is $\rho_W^{\rm in} \sim \sigma H_i$. From this epoch onward the energy density of the Universe is assumed to be dominated by heavy relics or an oscillating modulus field and in both the cases the scale factor grows as $a(t) \propto t^{2/3}$. The energy density scales as $\rho_{\rm mod} \sim \rho_{\rm mod}^{\rm in}/(a(t))^3$. If the domain wall (DW) complex remains frustrated, i.e., its energy density contribution $\rho_{\rm DW} \propto 1/a(t)$, the Hubble parameter at the epoch of equality of DW contribution with that of the rest of the matter is given by [16]

$$H_{\rm eq} \sim \sigma^{3/4} H_i^{1/4} M_{\rm Pl}^{-3/2}. \tag{3}$$

Assuming that the domain walls start decaying as soon as they dominate the energy density of the Universe, which corresponds to a temperature T_D such that $H_{\rm eq}^2 \sim GT_D^4$, the above equation gives

$$T_D^4 \sim \sigma^{3/2} H_i^{1/2} M_{\rm Pl}^{-1}. \tag{4}$$

Under the assumption that the domain walls are formed at $T \sim \sigma^{1/3}$

$$H_i^2 = \frac{8\pi}{3} G\sigma^{4/3} \sim \frac{\sigma^{4/3}}{M_{\rm Pl}^2}. \tag{5}$$

Now from Eq. (4)

$$T_D^4 \sim \frac{\sigma^{11/6}}{M_{\rm Pl}^{3/2}} \sim \frac{M_R^{11/2}}{M_{\rm Pl}^{3/2}} \sim M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{3/2}. \tag{6}$$

Demanding $\delta\rho > T_D^4$ leads to

$$\delta\rho > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{3/2}. \tag{7}$$

The third possibility is the walls dominating the energy density of the Universe for a limited epoch which leads to a mild inflation. This possibility was considered in Refs. [17,18]. As discussed in Ref. [5], the evolution of energy density of such walls can be expressed as

$$\rho_{\rm DW}(t_d) \sim \rho_{\rm DW}(t_{\rm eq}) \left(\frac{a_{\rm eq}}{a_d}\right), \tag{8}$$

where $a_{\rm eq}(a_d)$ is the scale factor at which domain walls start dominating (decaying) and $t_{\rm eq}(t_d)$ is the corresponding time. If the epoch of domain-wall decay is characterized by temperature T_D, then $\rho_{\rm DW} \sim T_D^4$ and the above equation gives

$$T_D^4 = \rho_{\rm DW}(t_{\rm eq}) \left(\frac{a_{\rm eq}}{a_d}\right). \tag{9}$$

In the MD era the energy density of the moduli fields scale as

$$\rho^d_{\rm mod} \sim \rho^{\rm eq}_{\rm mod}\left(\frac{a_{\rm eq}}{a_d}\right)^3. \tag{10}$$

Using this in Eq. (9) gives

$$\rho^d_{\rm mod} \sim \frac{T_D^{12}}{\rho^2_{\rm DW}(t_{\rm eq})}. \tag{11}$$

Domain walls start dominating the Universe after the time of equality, $\rho_{\rm DW}(t_d) > \rho^d_{\rm mod}$. So the pressure difference across the walls when they start decaying is given by

$$\delta\rho \geq \frac{T_D^{12}G^2}{H^4_{\rm eq}}, \tag{12}$$

where $H^2_{\rm eq} \sim G\rho_{\rm DW}(t_{\rm eq})$. Replacing the value of $H_{\rm eq}$ from Eq. (3), the pressure difference becomes

$$\delta\rho \geq M_R^4\frac{T_D^{12}M^3_{\rm Pl}}{M_R^{15}}. \tag{13}$$

Unlike the previous two cases RD and MD, here it will not be possible to estimate T_D in terms of other mass scales and we will keep it as undetermined.

III. MINIMAL LEFT-RIGHT SYMMETRIC MODEL

A. LRSM with Higgs doublets

We first study the left-right symmetric extension of the standard model with only Higgs doublets. In addition to the usual fermions of the standard model, we require the right-handed neutrinos to complete the representations. One of the important features of the model is that it allows spontaneous parity violation. The Higgs representations then require a bidoublet field, which breaks the electroweak symmetry and gives masses to the fermions. But the neutrinos can have Dirac masses only, which are then expected to be of the order of charged fermion masses. To implement the seesaw mechanism and obtain the observed tiny masses of the standard model neutrinos naturally, one has to introduce fermion triplets to give rise to the so-called type III seesaw mechanism [19]. However, we shall restrict ourselves to the scalar sector and shall not discuss the implications of such additional fermions.

The particle content of the left-right symmetric model with Higgs doublet is

$$\begin{aligned}
\text{Fermions: } & Q_L \equiv (3,2,1,1/3), && Q_R \equiv (3,1,2,1/3),\\
& \Psi_L \equiv (1,2,1,-1), && \Psi_R \equiv (1,1,2,-1)\\
\text{Scalars: } & \Phi \equiv (1,2,2,0), && H_L \equiv (1,2,1,1),\\
& H_R \equiv (1,1,2,1),
\end{aligned}$$

where the numbers in the brackets are the quantum numbers corresponding to the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. In addition to the bidoublet scalar field Φ, we should also have two doublet fields H_L and H_R to break the left-right symmetry and contribute to the neutrino masses. Thus the symmetry breaking pattern becomes

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle H_R\rangle} SU(2)_L \times U(1)_Y \xrightarrow{\langle\Phi\rangle} U(1)_{em}.$$

B. LRSM with Higgs triplets

In this section we briefly outline left-right symmetric models with different field contents than the one in the previous section. The usual fermions, including the right-handed neutrinos, belong to the similar representations as in the previous section. However, the scalar sector now contains triplet Higgs scalars in addition to the bidoublet Higgs scalar to break the left-right symmetry. The triplet Higgs scalars can then give Majorana masses to the standard model neutrinos by the so-called type II seesaw mechanism [4].

The particle content of LRSM with Higgs triplets is

$$\begin{aligned}
\text{Fermions: } & Q_L \equiv (3,2,1,1/3), && Q_R \equiv (3,1,2,1/3),\\
& \Psi_L \equiv (1,2,1,-1), && \Psi_R \equiv (1,1,2,-1)\\
\text{Scalars: } & \Phi \equiv (1,2,2,0), && \Delta_L \equiv (1,3,1,2),\\
& \Delta_R \equiv (1,1,3,2).
\end{aligned}$$

The symmetry breaking pattern in this model remains the same as in the previous model although the structure of neutrino masses changes. In the symmetry breaking pattern, the scalar Δ_R now replaces the role of H_R, but otherwise there is no change.

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle \Delta_R\rangle} SU(2)_L \times U(1)_Y \xrightarrow{\langle\Phi\rangle} U(1)_{em}.$$

C. Constraints on M_R from domain wall disappearance

In both versions of minimal LRSM discussed above, the nonzero vev of the right-handed doublet (or triplet) field breaks both $SU(2)_R \times U(1)_{B-L}$ gauge symmetry as well as the discrete left-right parity (or D parity) and hence gives rise to transitory domain walls. In this section, we consider explicit D-parity-breaking Planck-suppressed operators in these models by adopting the technique developed in Ref. [5]. And we find constraints on the parity breaking scale by demanding that these Planck-suppressed operators give rise to successful disappearance of domain walls.

In both the minimal versions of LRSM discussed above, the leading nonrenormalizable operator is of dimension six which can be written as

$$V_{\rm NR} \supset f_L\frac{(\Sigma_L^\dagger\Sigma_L)^3}{M^2_{\rm Pl}} + f_R\frac{(\Sigma_R^\dagger\Sigma_R)^3}{M^2_{\rm Pl}}, \tag{14}$$

where Σ can either be a Higgs doublet or a Higgs triplet. Assuming a phase where only right-type fields get nonzero vev and left-type fields get zero vev, the scalar potential up to the leading term in $1/M^2_{\rm Pl}$ becomes

$$V_{\rm eff}^R \sim \frac{f_R}{M_{\rm Pl}^2} M_R^6. \tag{15}$$

Similarly assuming nonzero vev for left-type fields only and not for right-type fields the effective potential becomes

$$V_{\rm eff}^L \sim \frac{f_L}{M_{\rm Pl}^2} M_L^6. \tag{16}$$

Because of the equal chance of both Σ_L and Σ_R acquiring the same vev (guaranteed by the presence of discrete left-right symmetry), we consider $M_L = M_R$. Thus, the effective energy difference across the walls separating these two vacua is given by

$$\delta\rho \sim \frac{(f_L - f_R)}{M_{\rm Pl}^2} M_R^6. \tag{17}$$

Now we shall compare this $\delta\rho$ with the case in a MD era where we have calculated the energy density for the domain wall to disappear,

$$\frac{(f_L - f_R)}{M_{\rm Pl}^2} M_R^6 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{3/2}. \tag{18}$$

Taking the dimensionless parameters f to be of order unity, the above equation gives a lower bound on M_R in a MD era

$$M_R > M_{\rm Pl}, \tag{19}$$

which is unnatural considering the fact that Planck scale is the maximum energy scale a physical theory can have. Similarly for the RD era

$$\frac{(f_L - f_R)}{M_{\rm Pl}^2} M_R^6 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{2}, \tag{20}$$

which does not give a bound on M_R. Rather it gives a lower bound $f_L - f_R > 1$. This is also unnatural since dimensionless couplings are generically taken to be of order one.

Thus, in both versions of minimal LRSM discussed above, the requirement of domain-wall disappearance gives rise to unnatural constraints on the scale of parity breaking and the dimensionless parameters. This drawback of such minimal models appeals for suitable extensions so as to guarantee successful disappearance of cosmologically unwanted domain walls. In this paper, we propose two such possible extensions as discussed in the next section.

IV. EXTENDED LRSM AND SUCCESSFUL DISAPPEARANCE OF DOMAIN WALLS

In this section, we propose two viable as well as minimal extensions of the left-right symmetric models discussed above. We show that, such extensions can give rise to the successful disappearance of domain walls and different symmetry breaking patterns as well as phenomenology.

A. Extension by a gauge singlet

Consider a gauge singlet field $\sigma(1,1,1,0)$ which is even under parity so that the tree-level Lagrangian is parity symmetric until the Σ_R field acquires a vev to break (spontaneously) parity as well as the $SU(2)_R \times U(1)_{B-L}$ gauge symmetry to $U(1)_Y$ of the standard model. To study the domain-wall disappearance mechanism in this model, we consider Planck suppressed higher-dimensional operators as in the previous section. Unlike before, here we can have dimension five Planck-suppressed terms in the scalar potential which, as we will see, create sufficient pressure difference across the domain walls to make them disappear. These operators can be written as

$$V_{\rm NR} \supset f_L \sigma \frac{(\Sigma_L^\dagger \Sigma_L)^2}{M_{\rm Pl}} + f_R \sigma \frac{(\Sigma_R^\dagger \Sigma_R)^2}{M_{\rm Pl}}, \tag{21}$$

where Σ can either be a Higgs doublet or a Higgs triplet and σ is the gauge singlet we have introduced. Since a singlet like $\sigma(1,1,1,0)$ can naturally fit inside several $SO(10)$ representations, we assume the vev of this singlet field to be of order $\langle\sigma\rangle \sim M_{\rm GUT} \sim 2 \times 10^{16}$ GeV. Assuming a phase where only right-type fields get nonzero vev and left-type fields get zero vev, the scalar potential up to the leading term in $1/M_{\rm Pl}$ becomes

$$V_{\rm eff}^R \sim \frac{f_R}{M_{\rm Pl}} M_{\rm GUT} M_R^4. \tag{22}$$

Similarly assuming nonzero vev for left-type fields only and not for right-type fields the effective potential becomes

$$V_{\rm eff}^L \sim \frac{f_L}{M_{\rm Pl}} M_{\rm GUT} M_L^4. \tag{23}$$

Because of the equal chance of both Σ_L and Σ_R acquiring the same vev, we consider $M_L = M_R$. Thus, the effective energy difference across the walls separating these two vacua is given by

$$\delta\rho \sim \frac{(f_L - f_R)}{M_{\rm Pl}} M_{\rm GUT} M_R^4. \tag{24}$$

Comparing this $\delta\rho$ with the case in a MD era, we have

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{\rm GUT} M_R^4 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{3/2}. \tag{25}$$

Taking the dimensionless parameters f to be of order unity, the above equation gives an upper bound on M_R in a MD era

$$M_R < (M_{\rm Pl} M_{\rm GUT}^2)^{1/3} \sim 10^{17}\ \text{GeV}. \tag{26}$$

Similarly for a RD era

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{\rm GUT} M_R^4 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{2}, \tag{27}$$

which gives a similar upper bound on M_R as

$$M_R < (M_{\rm Pl} M_{\rm GUT})^{1/2} \sim 10^{17}\ \text{GeV}. \quad (28)$$

Comparing the obtained $\delta\rho$ with the weak inflation case we have

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{\rm GUT} M_R^4 \geq M_R^4 \frac{T_D^{12} M_{\rm Pl}^3}{M_R^{15}}. \quad (29)$$

Taking the dimensionless coefficients to be of order one, we arrive at the following bound on M_R:

$$M_R \geq 1 \times 10^4 T_D^{4/5}. \quad (30)$$

Thus, for T_D of the electroweak scale, $M_R > 4 \times 10^5$ GeV.

B. Extension by a pair of Higgs triplets: Introducing multistep symmetry breaking

In this section, we discuss another possibility to make the domain walls disappear in minimal LRSM by introducing an additional pair of Higgs triplets $\Omega_L(1, 3, 1, 0)$, $\Omega_R(1, 1, 3, 0)$. As we will see, this extra pair of fields not only provides a viable mechanism for domain-wall disappearance, but also allows the possibility to achieve the symmetry breaking $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ at two different stages:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ \xrightarrow{\langle\Omega_R\rangle} SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow{\langle\Sigma_R\rangle} SU(2)_L \times U(1)_Y,$$

where Σ can either be a Higgs doublet or a Higgs triplet. Unlike in the case of minimal LRSM, here we can have dimension five Planck-suppressed terms in the scalar potential which, as we will see, create sufficient pressure difference across the domain walls to make them disappear. These operators can be written as

$$V_{\rm NR} \supset \frac{f_L}{M_{\rm Pl}} (\Omega_L^\dagger \Omega_L)\left(\Sigma_L^\dagger \Omega_L \Sigma_L\right) + \frac{f_R}{M_{\rm Pl}} (\Omega_R^\dagger \Omega_R)\left(\Sigma_R^\dagger \Omega_R \Sigma_R\right). \quad (31)$$

We denote the vev of Σ_R as the scale of $U(1)_{B-L}$ symmetry breaking M_{B-L} and that of Ω_R as M_R. Assuming nonzero vev for only the right-handed Higgs fields and zero vev for the left-handed ones, the effective potential becomes

$$V_{\rm eff}^R \sim \frac{f_R}{M_{\rm Pl}} M_{B-L}^2 M_R^3. \quad (32)$$

Similarly, assuming only the left-type Higgs to acquire nonzero vev, we have the effective potential as

$$V_{\rm eff}^L \sim \frac{f_L}{M_{\rm Pl}} M_{B-L}^2 M_R^3. \quad (33)$$

The energy difference across the walls separating the left-hand and the right-hand sectors is nothing but $V_{\rm eff}^L - V_{\rm eff}^R$:

$$\delta\rho \sim \frac{(f_L - f_R)}{M_{\rm Pl}} M_{B-L}^2 M_R^3. \quad (34)$$

Comparing this $\delta\rho$ with the pressure difference needed for the domain walls to disappear during a MD, we get

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{B-L}^2 M_R^3 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^{3/2}. \quad (35)$$

Taking the dimensionless parameters f to be of order unity, the above equation gives an upper bound on M_R in a MD era

$$M_R < (M_{\rm Pl} M_{B-L}^4)^{1/5}. \quad (36)$$

Similarly for RD era

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{B-L}^2 M_R^3 > M_R^4 \left(\frac{M_R}{M_{\rm Pl}}\right)^2, \quad (37)$$

which gives a similar upper bound on M_R as

$$M_R < (M_{\rm Pl} M_{B-L}^2)^{1/3}. \quad (38)$$

Thus, for a TeV scale M_{B-L}, the scale of parity breaking M_R has to be less than 10^6 GeV and 10^8 GeV for the MD and RD eras respectively. Comparing the obtained $\delta\rho$ with the weak inflation case we have

$$\frac{(f_L - f_R)}{M_{\rm Pl}} M_{B-L}^2 M_R^3 \geq M_R^4 \frac{T_D^{12} M_{\rm Pl}^3}{M_R^{15}}. \quad (39)$$

Taking the dimensionless coefficients to be of order one, we arrive at the following bound on M_R:

$$M_R \geq 2.7 \times 10^5 T_D^{2/7} M_{B-L}^{-1/7}. \quad (40)$$

V. GAUGE COUPLING UNIFICATION

The one-loop renormalization group evolution equations [20] are given by

$$\mu \frac{dg_i}{d\mu} = \beta_i(g_i) = \frac{g_i^3}{16\pi^2} b_i. \quad (41)$$

Defining $\alpha_i = g_i^2/(4\pi)$ and $t = \ln(\mu/\mu_0)$ and the most general renormalization group equation above becomes

$$\frac{d\alpha_i^{-1}}{dt} = -\frac{b_i}{2\pi}. \quad (42)$$

The one-loop beta function is given by

$$\beta_i(g_i) = \frac{g_i^3}{16\pi^2}\left[-\frac{11}{3}\mathrm{Tr}[T_a^2] + \frac{2}{3}\sum_f \mathrm{Tr}[T_f^2] + \frac{1}{3}\sum_s \mathrm{Tr}[T_s^2]\right], \quad (43)$$

where f and s denote the fermions and scalars respectively. For $SU(N)$, $\mathrm{Tr}[T_a^2] = N$ and $\mathrm{Tr}[T_i T_i] = \frac{1}{2}$. We closely

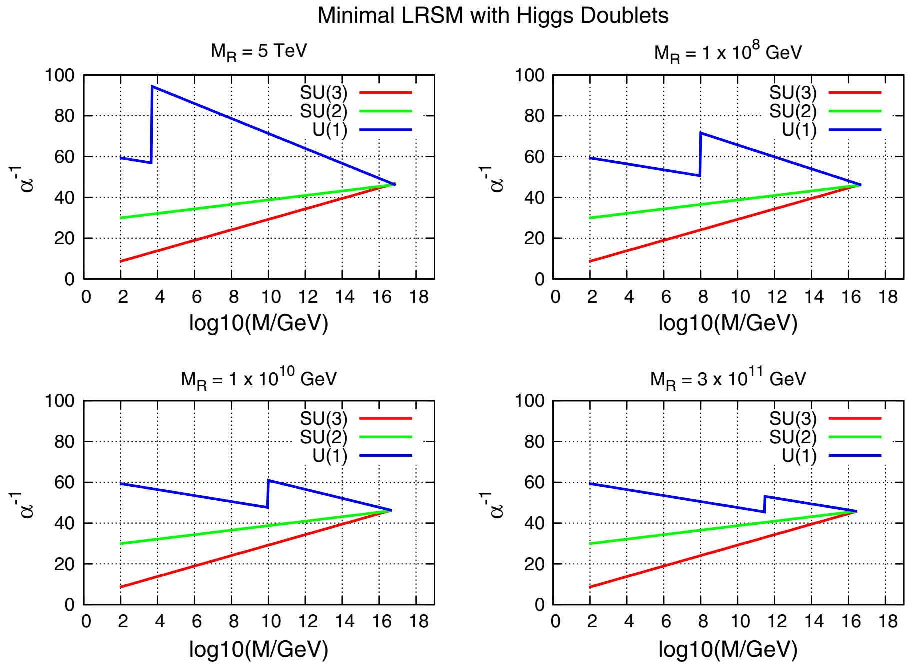

FIG. 1 (color online). Gauge coupling unification in minimal LRSM with Higgs doublets. Including the presence of an extra pair of fields (1, 1, 1, 2), (1, 1, 1, −2) allows the possibility to have low-scale M_R. The four plots correspond to the number of such extra pairs $n = 6, 4, 2, 0$ respectively.

follow the analysis in Ref. [12] to calculate the beta functions in both the minimal as well as extended LRSM discussed above. The experimental initial values for the couplings at electroweak scale $M = M_Z$ [21] are

$$\begin{pmatrix} \alpha_3(M_Z) \\ \alpha_2(M_Z) \\ \alpha_1(M_Z) \end{pmatrix} = \begin{pmatrix} 0.118 \pm 0.003 \\ 0.033493^{+0.000042}_{-0.000038} \\ 0.016829 \pm 0.000017 \end{pmatrix}. \qquad (44)$$

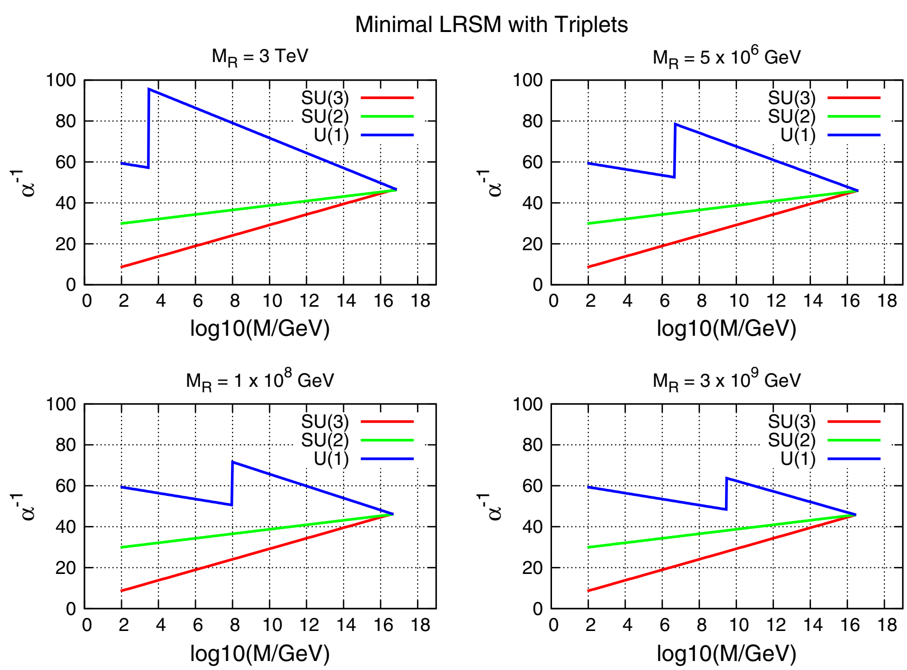

FIG. 2 (color online). Gauge coupling unification in minimal LRSM with Higgs triplets. Including the presence of an extra pair of fields (1, 1, 1, 2) (1, 1, 1, −2) allows the possibility to have low-scale M_R. The four plots correspond to the number of such extra pairs $n = 3, 2, 1, 0$ respectively.

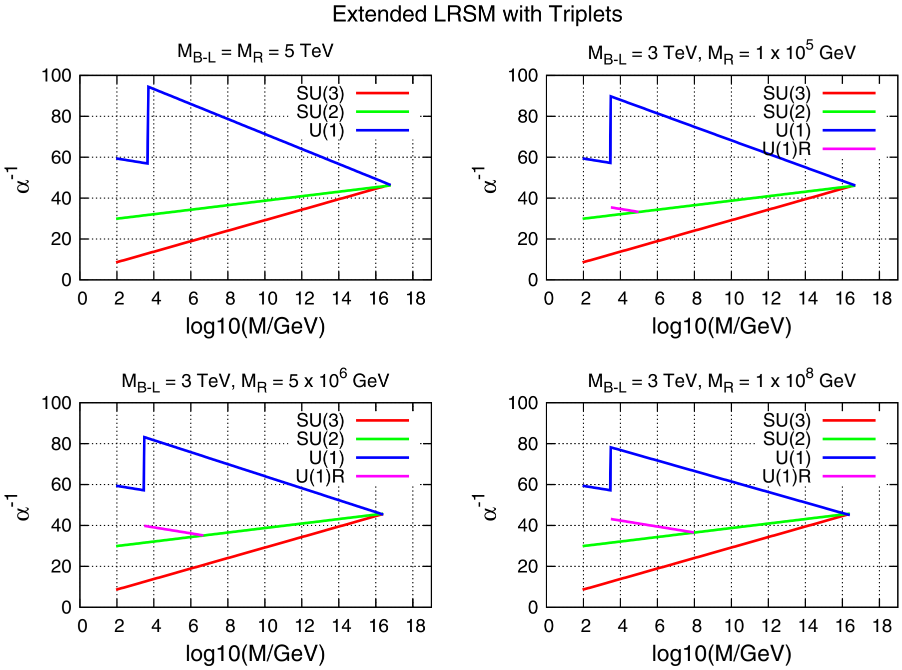

FIG. 3 (color online). Gauge coupling unification in extended LRSM with Higgs triplets. Including the presence of an extra pair of fields (1, 1, 1, 2), (1, 1, 1, −2) allows the possibility to have low-scale M_R. The four plots correspond to the number of such extra pairs $n = 3, 2, 1, 0$ respectively.

The normalization condition at $M = M_R(M = M_{B-L})$ where the $U(1)_Y$ gauge coupling merge with $SU(2)_R \times U(1)_{B-L}(U(1)_R \times U(1)_{B-L})$ is $\alpha_{B-L}^{-1} = \frac{5}{2}\alpha_Y^{-1} - \frac{3}{2}\alpha_L^{-1}$. Using all these, the gauge-coupling unification for minimal LRSM with doublets and triplets are shown in Figs. 1 and 2 respectively. We show that, just with the minimal field content and no additional fields, successful gauge-coupling unification can be achieved only when the parity breaking scale M_R is as high as 3×10^{11} GeV and 3×10^9 GeV for doublet and triplet model respectively. However, if extra pairs of fields $\chi(1, 1, 1, 2)$, $\bar{\chi}(1, 1, 1, -2)$ are taken into account, the scale of parity breaking M_R can be as low as a few TeV's as can be seen from Figs. 1 and 2. These extra fields although looking unnatural (if large in numbers), can naturally fit inside $SO(10)$ representations like **120**.

Similarly, for the extended LRSM discussed in Sec. IV we study the gauge-coupling unification and show that with just $\Delta_{L,R}$, $\Omega_{L,R}$ as the Higgs content apart from the usual bidoublet, gauge-coupling unification can be achieved for the symmetry breaking scales $M_{B-L} = 3$ TeV, $M_R = 10^8$ GeV as can be seen from Fig. 3. Such a possibility of a TeV scale $U(1)_{B-L}$ gauge symmetry is quite tantalizing in view of the ongoing collider experiments like the Large Hadron Collider (LHC). The scale of parity breaking M_R can be lowered further by incorporating additional fields like χ, $\bar{\chi}$ as discussed in the case of minimal LRSM. We find that for three such additional pairs of fields, both M_{B-L} and M_R can be as low as a few TeV's.

VI. RESULTS AND CONCLUSION

We have studied the domain-wall formation as a result of spontaneous breaking of a discrete symmetry called D parity in generic left-right symmetric models. Since stable domain walls are in conflict with cosmology, we consider the effects of Planck-scale suppressed operators in destabilizing them. We consider the evolution and decay of domain walls in two different epochs: radiation dominated as well as matter dominated. We find that in minimal versions of these models, the successful removal of domain walls put such constraints on the D-parity breaking scale M_R, which are not possible to

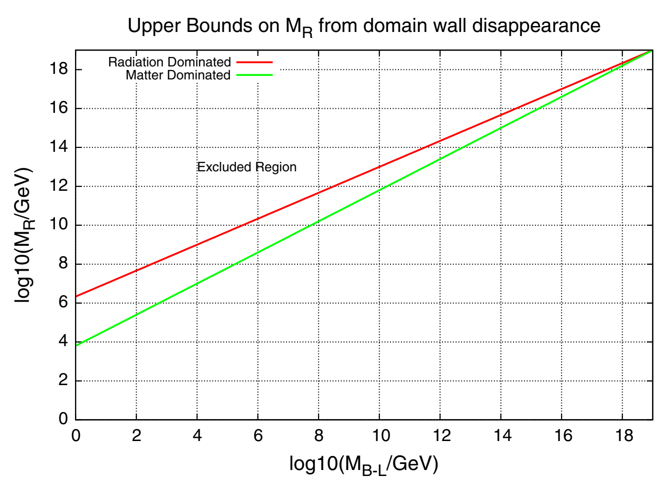

FIG. 4 (color online). Upper bound on M_R from successful domain-wall disappearance as a function of M_{B-L}.

TABLE I. Bounds on M_R/GeV in left-right symmetric models.

Model	Gauge-coupling unification	DW removal during MD era	DW removal during RD era	DW removal including WI
Minimal doublet	$\sim 3\times 10^{11}$	$>M_{\rm Pl}$	$f_L - f_R > 1$	$\geq 3.7\times 10^{13} T_D^{12/17}$
Minimal triplet	$\sim 3\times 10^{9}$	$>M_{\rm Pl}$	$f_L - f_R > 1$	$\geq 3.7\times 10^{13} T_D^{12/17}$
Extended singlet	$\sim 3\times (10^9\text{–}10^{11})$	$<10^{17}$	$<10^{17}$	$\geq 1\times 10^{4} T_D^{4/5}$
Extended triplet	$\sim 1\times 10^{8}$	$<(M_{\rm Pl}M_{B-L}^4)^{1/5}$	$<(M_{\rm Pl}M_{B-L}^2)^{1/3}$	$\geq 2.7\times 10^{5} T_D^{2/7} M_{B-L}^{-1/7}$

realize in any physical theory, for example $M_R > M_{\rm Planck}$. We also study gauge-coupling unification in minimal versions of these models and find that with the minimal field content M_R has to be as high as 10^9–10^{11} GeV (far beyond the reach of present experiments) for successful gauge-coupling unification to be achieved.

To have successful domain-wall disappearance as well as to explore the possibility of a TeV scale intermediate symmetry, we study two viable extension of minimal LRSM: one with a gauge singlet and one with a pair of triplets with $U(1)_{B-L}$ charge zero. A gauge singlet although it does not affect the running of gauge coupling, contributes to the effective energy density in such a way that sufficient pressure difference can be created across the domain walls to make them disappear without having some unphysical constraints like $M_R > M_{\rm Planck}$ as in the case of minimal LRSM. Extension by Higgs triplets $\Omega_{L,R}$ not only provides a solution to the domain wall problem, but also allows the possibility to have separate $SU(2)_R$ and $U(1)_{B-L}$ symmetry breaking scales. This allows us to have a TeV scale $U(1)_{B-L}$ symmetry even if the scale of parity breaking M_R is restricted to be as high as 10^8 GeV. However, to agree with the constraints coming from domain-wall disappearance ($M_R < 10^6$–10^8 GeV for TeV scale M_{B-L}), we have to incorporate additional pairs of fields $\chi(1,1,1,2)$, $\bar{\chi}(1,1,1,-2)$ as seen from Fig. 3. These extra pairs of fields can naturally fit inside $SO(10)$ representations like **120**. The constraints on the scale of parity breaking M_R from domain-wall disappearance in this model also depends on the scale of $U(1)_{B-L}$ symmetry breaking M_{B-L}. We show the upper bound on M_R as a function of M_{B-L} in Fig. 4 for both MD and RD eras. A brief summary of our results is presented in the Table I.

To summarize the results of our paper, we have shown that in the minimal versions of nonsupersymmetric left-right models, successful domain-wall disappearance can not be achieved. However, we can achieve successful gauge-coupling unification with the minimal field content if the scale of parity breaking is as high as 10^9–10^{11} GeV which can be lowered further by incorporating additional fields. Hence suitable extensions of minimal LRSM are required to achieve both domain-wall disappearance as well as gauge-coupling unification together with the tantalizing possibility of a TeV scale intermediate symmetry. We propose two such extensions and show that in the Higgs triplet extension of minimal LRSM, all these possibilities can be realized simultaneously.

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