Spontaneous Parity Violation in a Supersymmetric Left-Right Symmetric Model

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Abstract

We propose a novel implementation of spontaneous parity breaking in supersymmetric left-right symmetric model, avoiding some of the problems encountered in previous studies. This implementation includes a bitriplet and a singlet, in addition to the bidoublets which extend the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM). The supersymmetric vacua of this theory are shown to lead generically to spontaneous violation of parity, while preserving R parity. The model is shown to reproduce the see-saw relation for vacuum expectation values, $v_L v_R \approx m_{EW}^2$ relating the new mass scales v_L, v_R to the electroweak scale m_{EW}, just as in the non-supersymmetric version. The scale v_R determines the mass scale of heavy majorana neutrinos, which gets related to the obeserved neutrino masses through type II see-saw relation.

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I. INTRODUCTION

The standard model (SM) has been successful in explaining the strong, the weak and the electromagnetic interactions at currently accessible energies. The only obvious indication of physics beyond the SM seems to be the observation of the neutrino mass. Yet there are several motivations to look for a comprehensive solution to a variety of puzzles of the SM. Left-Right symmetric model [1, 2, 3, 4, 5] has since long received considerable attention as a simple extension of the SM. While chirality is an elegant ingredient of nature which prevents unduly large masses for fermions, most of nature is left-right symmetric, suggesting the reasonable hypothesis that parity is only spontaneously broken, a principle built into the left-right symmetric models. Due to inclusion of right handed neutrino states as a principle, such models provide a natural explanation for the smallness of neutrino masses [6, 7, 8, 9] via see-saw mechanism [10, 11, 12, 13]. This class of models also provides a natural embedding of electroweak hypercharge, giving a physical explanation for the required extra $U(1)$ as being generated by the difference between the baryon number (B) and the lepton number (L). Thus, $B - L$, the only exact global symmetry of SM becomes a gauge symmetry, ensuring its exact conservation, in turn leading to several interesting consequences.

The other extension of the standard model is the grand unified theory, which unifies all the gauge groups into a single simple group at very high energy with only one gauge coupling constant to explain all the three low energy interactions. The quark-lepton unification then predicts proton decay, charge quantization, etc. However, the high energy scale leads to the gauge hierarchy problem, which dictates the inclusion of supersymmetry as a key ingredient. In order to protect the electroweak scale from the unification scales, the minimal supersymmetric standard model (MSSM) would be the most logical extension of the standard model. Its prediction of particles at energies accessible to current colliders makes the model of immediate interest. The SM predictions now get enriched by the additional predictions of supersymmetry, but to prevent the unwanted predictions like proton decay, one needs to impose the R-parity symmetry, defined in terms of the gauged $(B - L)$ quantum number [14, 15], as

$$R = (-1)^{3(B-L)+2S}. \tag{1}$$

In the class of supersymmetric left-right models where the parity breakdown is signalled by the vacuum expectation values of triplet Higgs scalars, the R-parity is naturally conserved and its origin gets related to the gauged $B - L$ symmetry [16].

The bare minimal anomaly free supersymmetric extension of the left-right symmetric model with triplet Higgs bosons leads to several nettlesome obstructions which may be considered to be a guidance towards a unique consistent theory. One of the most important problems is the spontaneous breaking of left-right symmetry [17, 18], viz., all vacuum expectation values breaking $SU(2)_L$ are exactly equal in magnitude to those breaking $SU(2)_R$, making the vacuum parity symmetric. There have been suggestions to solve this problem by introducing additional fields, or higher dimensional operators, or by going through a different symmetry breaking chain or breaking the left-right symmetry along with the supersymmetry breaking [17, 18, 19, 20, 21, 22, 23]. In some cases, when the problem is cured through the introduction of a parity-odd singlet, the soft susy breaking terms lead to breaking of electromagnetic charge invariance. A recent improvement [19] using a parity even singlet may however deviate significantly from MSSM, and remains to be explored fully for its phenomenological consistency. Further, in the minimal SUSYLR model with minimal Higgs fields, which has been studied extensively [16, 17, 18], it has been found that global minimum of the Higgs potential is either charge violating or R-parity violating. In this article we propose yet another solution to the problem, which resembles the non-supersymmetric solution, relating the vacuum expectation values (*vev*s) of the left-handed and right-handed triplet Higgs scalars to the Higgs bi-doublet *vev* through a seesaw relation. The left-right symmetry breaking scale thus becomes inversely proportional to the left-handed triplet Higgs scalar that gives the type II seesaw masses to the neutrinos. The novel feature consists in the introduction of a bitriplet Higgs and another Higgs singlet under left-right group. The vacuum that preserves both electric charge and R-parity can naturally be the global minimum of the full potential. The most attractive feature of the present model is that generically it does not allow a left-right symmetric vacuum, though the latter appears as a single point within the flat direction of the minima respecting supersymmetry. When the flat direction is lifted all the energy scales required to explain phenomenology result naturally. This model can be embedded in the minimal supersymmetric SO(10) grand unified theory.

Section (II) recapitulates the minimal supersymmetric left-right model for completeness of the paper. In section (III) we discuss the proposed new model of supersymmetry having an additional bi-triplet and a singlet. Section (IV) discusses the phenomenology of this proposed model. Finally, section (V) gives the conclusion.

II. MINIMAL SUPERSYMMETRIC LEFT-RIGHT MODEL: A RECAP

In this section we briefly describe the minimal supersymmetric left-right model. In the left-right symmetric models, it is assumed that the MSSM gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is enhanced at some higher energy, when the left-handed and right-handed fermions are treated on equal footing. The minimal supersymmetric left-right (SUSYLR) model has the gauge group $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ which could emerge from a supersymmetric $SO(10)$ grand unified theory. The model has three generations of quarks and leptons, and their transformations are given by,

$$
\begin{aligned}
Q &= (3, 2, 1, 1/3), \qquad & Q^c &= (3^*, 2, 1, -1/3), \\
L &= (1, 2, 1, -1), \qquad & L^c &= (1, 1, 2, 1),
\end{aligned}
\tag{2}
$$

where, the numbers in the brackets denote the quantum numbers under $SU(3)_c$, $SU(2)_L$, $SU(2)_R$, $U(1)_{B-L}$. We have omitted the generation index for simplicity of notation.

The left-right symmetry could be broken by either doublet Higgs scalars or triplet Higgs scalar. It has been argued that for a minimal choice of parameters, it is convenient to break the group with a triplet Higgs scalar. We shall consider here the minimal Higgs sector, which consists of

$$
\begin{aligned}
\Delta &= (1, 3, 1, 2), \qquad & \bar{\Delta} &= (1, 3, 1, -2), \\
\Delta^c &= (1, 1, 3, -2), \qquad & \bar{\Delta}^c &= (1, 1, 3, 2), \\
\Phi_i &= (1, 2, 2^*, 0), \qquad & (i &= 1, 2).
\end{aligned}
\tag{3}
$$

As pointed out in [16] the bidoublets are doubled to achieve a nonvanishing Cabibbo-Kobayashi-Maskawa (CKM) quark mixing and the number of triplets is doubled for the sake of anomaly cancellation. Left-right symmetry is implemented in these theories as a discrete parity transformation as

$$
\begin{aligned}
& Q \longleftrightarrow Q_c^*, \quad L \longleftrightarrow L_c^*, \quad \Phi \longleftrightarrow \Phi^\dagger \\
& \Delta \longleftrightarrow \Delta^{c*}, \;\; \bar{\Delta} \longleftrightarrow \bar{\Delta}^{c*}.
\end{aligned}
\tag{4}
$$

The superpotential for this theory is given by

$$
\begin{aligned}
W &= Y^{(i)_q} Q^T \tau_2 \Phi_i \tau_2 Q^c + Y^{(i)_l} L^T \tau_2 \Phi_i \tau_2 L^c \\
&+ i(f L^T \tau_2 \Delta L + f^* L^{cT} \tau_2 \Delta^c L^c) \\
&+ \mu_\Delta \mathrm{Tr}(\Delta \bar{\Delta}) + \mu_\Delta^* \mathrm{Tr}(\Delta^c \bar{\Delta}^c) + \mu_{ij} \mathrm{Tr}(\tau_2 \Phi_i^T \tau_2 \Phi_j).
\end{aligned} \tag{5}
$$

All couplings $Y^{(i)_{q,l}}$, μ_{ij}, μ_Δ, f in the above potential, are complex with the the additional constraint that μ_{ij}, f and f^* are symmetric matrices. It is clear from the above eq. that the theory has no baryon or lepton number violation terms. As such R-parity symmetry, defined by $(-1)^{3(B-L)+2S}$, is automatically conserved in the SUSYLR model.

It turns out that left-right symmetry imposes rather strong constraints on the ground state of this model. It was pointed out by Kuchimanchi and Mohapatra [17] that there is no spontaneous parity breaking for this minimal choice of Higgs in the supersymmetric left-right model and as such the ground state remains parity symmetric. If parity odd singlets are introduced to break this symmetry [24], then it was shown [17] that the charge-breaking vacua have a lower potential than the charge-preserving vacua and as such the ground state does not conserve electric charge. Breaking R parity was another possible solution to this dilemma of breaking parity symmetry. However, if one wants to prevent proton decay, then one must look for alternative solutions. One such possible solution is to add two new triplet superfields $\Omega(1,3,1,0)$, $\Omega_c(1,1,3,0)$ where under parity symmetry $\Omega \leftrightarrow \Omega_c^*$. This field has been explored extensively in [16, 20, 21, 22, 23, 25].

In the present paper we discuss another alternative solution with the inclusion of a scalar bitriplet (η) and a parity odd singlet (σ). This model breaks parity spontaneously, and also preserves electromagnetic charge automatically. The left-right parity is spontaneously broken and as a result, the minimization does not allow a left-right symmetry preserving solution.

III. SUPERSYMMETRIC LEFT-RIGHT SYMMETRIC MODEL INCLUDING THE BI-TRIPLET AND THE SINGLET

We now present our model, where we include a bi-triplet and a parity odd singlet fields, in the minimal supersymmetric left-right symmetric model. These fields are vector-like and hence do not contribute to anomaly, so we consider only one of these fields. The quantum numbers for the new scalar fields η and σ, under the gauge group considered are given by,

$$\eta(1,3,3,0), \qquad \sigma(1,1,1,0). \tag{6}$$

Under parity, these fields transform as $\eta \leftrightarrow \eta$ and $\sigma \leftrightarrow -\sigma$. The superpotential for the model is written in the more general tensorial notation,

$$\begin{aligned} W \;=\; & f \eta_{\alpha i}\, \Delta_\alpha\, \Delta_i^c + f^* \eta_{\alpha i}\, \bar{\Delta}_\alpha\, \bar{\Delta}_i^c \\ & + \lambda_1\, \eta_{\alpha i}\, \Phi_{am}\, \Phi_{bn}\, (\tau^\alpha \epsilon)_{ab} \left(\tau^i \epsilon\right)_{mn} + m_\eta\, \eta_{\alpha i}\, \eta_{\alpha i} \\ & + M\, \left(\Delta_\alpha \bar{\Delta}_\alpha + \Delta_i^c \bar{\Delta}_i^c\right) + \mu\, \epsilon_{ab}\, \Phi_{bm}\, \epsilon_{mn}\, \Phi_{an} \\ & + m_\sigma\, \sigma^2 + \lambda_2\, \sigma \left(\Delta_\alpha \bar{\Delta}_\alpha - \Delta_i^c \bar{\Delta}_i^c\right), \end{aligned} \tag{7}$$

where, α, $\beta = 1,2,3$ and $a, b = 1,2$ are $SU(2)_L$ indices, whereas $i, j = 1,2,3$ and $m, n = 1,2$ are $SU(2)_R$ indices. The summation over repeated index is implied, with the change in basis from numerical $1,2,3$ indices to $+,-,0$ indices as follows,

$$\begin{aligned} \Psi_\alpha \Psi_\alpha \;&=\; \Psi_1\Psi_1 + \Psi_2\Psi_2 + \Psi_3\Psi_3 \\ &=\; \Psi_+\Psi_- + \Psi_-\Psi_+ + \Psi_0\Psi_0, \end{aligned} \tag{8}$$

where, we have defined $\Psi_\pm = (\Psi_1 \pm i\Psi_2)/\sqrt{2}$ and $\Psi_0 = \Psi_3$. The vacuum expectation values (vev) that the neutral components of the Higgs sector acquires are,

$$\begin{aligned} &\langle \Delta_- \rangle = \langle \bar{\Delta}_+ \rangle = v_L, && \langle \Delta_+^c \rangle = \langle \bar{\Delta}_-^c \rangle = v_R, \\ &\langle \Phi_{+-} \rangle = v, && \langle \Phi_{-+} \rangle = v', \\ &\langle \eta_{+-} \rangle = u_1, && \langle \eta_{-+} \rangle = u_2, \\ &\langle \eta_{00} \rangle = u_0. && \end{aligned} \tag{9}$$

Assuming SUSY to be unbroken till the TeV scale implies the F and D flatness conditions for the scalar fields to be,

$$\begin{aligned} F_{\Delta_\alpha} \;&=\; f\, \eta_{\alpha i}\, \Delta_i^c + M \bar{\Delta}_\alpha + \lambda_2\, \sigma\, \bar{\Delta}_\alpha = 0, \\ F_{\bar{\Delta}_\alpha} \;&=\; f^*\, \eta_{\alpha i}\, \bar{\Delta}_i^c + M \Delta_\alpha + \lambda_2\, \sigma\, \Delta_\alpha = 0, \\ F_{\Delta_i^c} \;&=\; f\, \eta_{\alpha i}\, \Delta_\alpha + M\, \bar{\Delta}_i^c - \lambda_2\, \sigma\, \bar{\Delta}_i^c = 0, \\ F_{\bar{\Delta}_i^c} \;&=\; f^*\, \eta_{\alpha i}\, \bar{\Delta}_i + M\, \Delta_i^c - \lambda_2\, \sigma\, \Delta_i^c = 0, \\ F_\sigma \;&=\; 2 m_\sigma\, \sigma + \lambda_2\, \left(\Delta_\alpha \bar{\Delta}_\alpha - \Delta_i^c \bar{\Delta}_i^c\right) = 0, \end{aligned}$$

$$
\begin{aligned}
F_{\eta_{\alpha i}} &= f\,\Delta_\alpha\,\Delta_i^c + f^*\bar{\Delta}_\alpha\,\bar{\Delta}_i^c + 2\,m_\eta\,\eta_{\alpha i} \\
&\quad + \lambda_1\,\Phi_{am}\,\Phi_{bn}(\tau^\alpha\epsilon)_{ab}(\tau^i\epsilon)_{mn} = 0,
\end{aligned}
$$

$$
\begin{aligned}
F_{\Phi_{cp}} &= \lambda_1\,\eta_{\alpha i}\Phi_{bn}\,(\tau^\alpha\epsilon)_{cb}\left(\tau^i\epsilon\right)_{pn} \\
&\quad + \lambda_1\,\eta_{\alpha i}\Phi_{am}\,(\tau^\alpha\epsilon)_{ac}(\tau^i\epsilon)_{mp} \\
&\quad + \mu\,\epsilon_{ac}\,\epsilon_{pn}\,\Phi_{an} + \mu\,\epsilon_{cb}\,\Phi_{bm}\,\epsilon_{mp} = 0, \qquad (10)
\end{aligned}
$$

$$
\begin{aligned}
D_{R_i} &= 2\Delta^{c\dagger}\tau_i\Delta^c + 2\bar{\Delta}^{c\dagger}\tau_i\bar{\Delta}^c + \eta\tau_i^T\eta^\dagger + \Phi\tau_i^T\Phi^\dagger = 0, \\
D_{L_i} &= 2\Delta^\dagger\tau_i\Delta + 2\bar{\Delta}^\dagger\tau_i\bar{\Delta} + \eta^\dagger\tau_i\eta + \Phi^\dagger\tau_i\Phi = 0, \\
D_{B-L} &= 2\left(\Delta^\dagger\Delta - \bar{\Delta}^\dagger\bar{\Delta}\right) - 2\left(\Delta^{c\dagger}\Delta^c - \bar{\Delta}^{c\dagger}\bar{\Delta}^c\right) = 0. \qquad (11)
\end{aligned}
$$

In the above eqns., we have neglected the slepton and squark fields, since they would have zero vev at the scale considered. We have also assumed $v' \ll v$ and hence the terms containing v' can be neglected.

IV. PHENOMENOLOGY

An inspection of the minimisation conditions obtained at the end of the previous section proves two important statements we have made earlier. First, the electromagnetic charge invariance of this vacuum is automatic for any parameter range of the theory. Secondly, the R-parity, defined in eq. (1), is preserved in the present model, since the Δ's are R-parity even whereas the bi-doublet and the bi-triplet Higgs scalars have zero R-parity.

We shall now discuss the conditions that emerge from the vanishing of the various F terms, which after the fields acquire their respective vevs, are given by,

$$F_\Delta = f\,u_1 v_R + (M + \lambda_2\langle\sigma\rangle)v_L = 0, \qquad (12)$$

$$F_{\bar{\Delta}} = f^* u_2 v_R + (M + \lambda_2\langle\sigma\rangle)v_L = 0, \qquad (13)$$

$$F_{\Delta^c} = f\,u_1 v_L + (M - \lambda_2\langle\sigma\rangle)v_R = 0, \qquad (14)$$

$$F_{\bar{\Delta}^c} = f^*\,u_2 v_L + (M - \lambda_2\langle\sigma\rangle)v_R = 0, \qquad (15)$$

$$F_\sigma = m_\sigma\,\langle\sigma\rangle + \lambda_2(v_L^2 - v_R^2) = 0, \qquad (16)$$

$$F_\eta = f\,v_L v_R + f^*\,v_L v_R + \lambda_1 v^2 + 2m_\eta(u_1 + u_2 + u_0) = 0, \qquad (17)$$

$$F_\Phi = -2\lambda_1(u_1 + u_2)v + 2\lambda_1 u_0 v - 2\mu v = 0. \qquad (18)$$

At the outset we see that the F_σ flatness condition permits the trivial solution $\langle\sigma\rangle = 0$, which would imply the undesirable solution $v_L = v_R$ and lead to no parity breakdown. But this special point can easily be destabilized once the soft terms are turned on. Away from this special point, we are led to phenomenologically interesting vacuum configurations.

The F flatness conditions for the Δ and $\bar{\Delta}$ fields demand $fu_1 = f^* u_2$ which can be naturally satisfied by choosing

$$f = f^* \qquad \text{and} \qquad u_1 = u_2 \equiv u. \tag{19}$$

This is consistent with the relation obtained from the F flatness conditions for the Δ^c and $\bar{\Delta}^c$ fields, which may now be together read as

$$(M - \lambda_2\langle\sigma\rangle)v_R = -f\, u v_L. \tag{20}$$

The first four conditions (12)-(15) can therefore be used to eliminate the scale u and give a relation

$$\left(\frac{v_L}{v_R}\right)^2 = \frac{M - \lambda_2\langle\sigma\rangle}{M + \lambda_2\langle\sigma\rangle}. \tag{21}$$

Let us assume the scale of the vev's u_1, u_2 and u_0 to be the same. Then the vanishing of F_η gives a relation

$$2f v_L v_R \approx -(\lambda_1 v^2 + 6m_\eta u). \tag{22}$$

Finally, the last condition (18) has an interesting consequence. While electroweak symmetry is assumed to remain unbroken in the supersymmetric phase, so that v must be chosen to be zero, we see that the factor multiplying v implies a relation

$$\mu \approx -\lambda_1 u. \tag{23}$$

That is, taking λ_1 to be order unity, the scale of the μ term determines the scale of u.

We now attempt an interpretation of these relations to obtain reasonable phenomenology. The scale v_R must be higher than the TeV scale. It seems reasonable to assume that the eq. (22) provides a see-saw relation between v_L and v_R vev's, and that this product is anchored by the TeV scale. Since bitriplet contributes additional non-doublet Higgs in the Standard Model, it is important that the vacuum expectation value u is much higher or much smaller than the electroweak scale, and we shall explore the latter route. In this case u should be strictly less than 1GeV. The scale m_η determines the masses of triplet majorons and needs to be high compared to the TeV scale. If the above see-saw relation is not to be jeopardized, we must have $m_\eta u \leq m_{EW}^2$. We can avoid proliferation of new mass scales by choosing

$$m_\eta u \approx v^2 = m_{EW}^2. \tag{24}$$

This establishes eq. (22) as the desired hierarchy equation, with f chosen to be negative.

Now let us examine the consistency of the assumption $u \ll m_{EW}$ in the light of the two equations (20) and (21). Let us assume that $(v_L/v_R) \ll 1$ as in the non-supersymmetric case. Then eq. (21) means that on the right hand side,

$$M - \lambda_2\langle\sigma\rangle \ll M + \lambda_2\langle\sigma\rangle \implies M \approx \lambda_2\langle\sigma\rangle. \tag{25}$$

Then eq. (12) can be read as

$$\frac{v_L}{v_R} \approx \frac{(-f)u}{2M}. \tag{26}$$

We thus see that the required hierarchies of scales can be spontaneously generated, and can be related to each other. Finally, although only the ratios has been related in eq. (26) we may choose

$$v_L \approx u, \qquad v_R \approx M. \tag{27}$$

We see that through this choice of individual scales and through the see-saw relation (22), u and v_R obey a mutual see-saw relation. A small value of u in the eV range would place v_R in the intermediate range as in the traditional proposals for neutrino mass see-saw. A larger range of values close to the GeV scale would lead to v_R and the resulting heavy neutrinos states within the range of collider confirmation.

Finally, returning to eq. (23), we can obtain the desirable scale for u by choosing μ to be of that scale, viz., in the sub-GeV range. This solves the μ problem arising in MSSM by relating it to other scales required to keep the v_R high. An interesting consequence of the choices made so far is that using eq.s (25) and (27) in eq. (16) yields

$$|m_\sigma| \approx \lambda_2 \frac{v_R^2}{\langle\sigma\rangle} \sim \lambda_2^2 M. \tag{28}$$

To summarize, various phenomenological considerations lead to a natural choice of three of the mass parameters of the superpotential, M, m_σ and m_η to be comparable to each other and large, such as to determine v_R, and in turn the masses of the heavy majorana neutrinos. The scale μ which determines the vacuum expectation value u and in turn the value v_L could be anything less than a GeV. Most importantly we have the see-saw relation eq. (22) which relates these scales, and if the v_R scale is to be within a few orders of magnitude of the TeV scale, then μ should be close to though less than a GeV.

We can contemplate two extreme possibilities for the scale M. Keeping in mind the gravitino production and overabundance problem, we can choose the largest value $v_R \leq 10^9$ GeV. If it can be ensured from inflation that this is also the reheat temperature, then the thermalisation of heavy majorana neutrinos required for thermal leptogenesis at a scale somewhat lower than this can be easily accommodated. We can also try to take v_R as low as 10 TeV which is consistent with preserving lepton asymmetry generated by non-thermal mechanisms [26]. Baryogenesis from non-thermal or sleptonic leptogenesis in this kind of setting has been extensively studied [27, 28, 29, 30]. This low value of v_R is consistent with neutrino see-saw relation, but will rely critically on the smallness of Yukawa couplings[26] and may be accessible to colliders [31].

As we have seen, at the large scale, charge conservation also demands conservation of R-parity. The question generally arise as to what happens when heavy fields are integrated out and soft supersymmetry breaking terms are switched on. The analysis done in [16] implies that if M_R is very large (around 10^{10} GeV), the breakdown of R-parity at low energy would give rise to an almost-massless majoron coupled to the Z-bosons, which is ruled out experimentally. This is one of the central aspects of supersymmetric left-right theories with large M_R: R-parity is an exact symmetry of the low energy effective theory. The supersymmetric partners of the neutrinos do not get any *vev* at any scale, which also ensures that the R-parity is conserved.

V. CONCLUSION

Supersymmetry and left-right symmetry are considered strong possible candidates for extension of standard model. However, construction of a low energy SUSYLR theory is by no means trivial, since left-right symmetry cannot be broken spontaneously [17]. In this paper, however, with the introduction of a bitriplet scalar field along with a parity odd Higgs singlet we have presented a possible mechanism of spontaneously breaking LR symmetry in a SUSYLR model. The advantages of this model besides breaking parity spontaneously is that it preserves R parity naturally. Also, we find a possible relation between the left-right symmetry breaking scale and the inverse of neutrino mass.

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