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Lepton parity in supersymmetric flavor models

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Abstract: We investigate supersymmetric models where neither R parity nor lepton number nor baryon number is imposed. The full high energy theory has an exact horizontal U(1) symmetry that is spontaneously broken. Quarks and Higgs fields carry integer horizontal charges but leptons carry half integer charges. Consequently, the effective low energy theory has two special features: a U(1) symmetry that is explicitly broken by a small parameter, leading to selection rules, and an exact residual Z_2 symmetry, that is lepton parity. As concerns neutrino parameters, the Z_2 symmetry forbids contributions from R_p-violating couplings and the U(1) symmetry induces the required hierarchy. As concerns baryon number violation, the Z_2 symmetry forbids proton decay and the U(1) symmetry provides sufficient suppression of double nucleon decay and of neutron − antineutron oscillations.

Keywords: Beyond Standard Model, Supersymmetric Standard Model, Neutrino Physics, Discrete and Finite Symmetries.

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Contents

1. Introduction

In contrast to the Standard Model (SM), the Supersymmetric Standard Model (SSM) does not have accidental lepton- (L) and baryon-number (B) symmetries. This situation leads to severe phenomenological problems, e.g. fast proton decay and large neutrino masses. The standard solution to this problem is to impose a discrete symmetry, R_p. The SSM with R_p does have L and B as accidental symmetries.

Both the SM and the SSM provide no explanation for the smallness and hierarchy in the Yukawa couplings. One way of explaining the flavor puzzle is to impose an approximate horizontal symmetry. Such symmetries suppress not only the Yukawa couplings but also the B and L violating terms of the SSM [1]–[16]. Consequently, it is possible to construct viable supersymmetric models with horizontal symmetries and without R_p. The phenomenology of these models is very different from that of R_p-conserving models. In particular, the LSP is unstable, various L and B violating processes may occur at an observable level, and an interesting pattern of neutrino masses is predicted.

It is not simple, however, to solve all problems of L and B violation by means of horizontal symmetries:

(a) Constraints from proton decay require uncomfortably large horizontal charges for quarks to sufficiently suppress the B violating terms [2];

(b) In models where the μ terms are not aligned with the B terms, constraints from neutrino masses require uncomfortably large horizontal charges for leptons to sufficiently suppress the L violating terms [3, 8].

Therefore, most models with horizontal symmetries and without R_p still impose baryon number symmetry and assume $\mu - B$ alignment at some high energy scale. In this work we show that it is not necessary to make these assumptions: one can construct viable supersymmetric models without R parity, without lepton number, without baryon number and with horizontal charges that are not very large. The crucial point is that the horizontal $\mathrm{U}(1)_H$ symmetry is not completely broken: a residual discrete symmetry, lepton parity, forbids proton decay and aligns the μ and B terms. The constraints on the baryon number violating terms from double nucleon decay and neutron-antineutron oscillations are easily satisfied and interesting neutrino parameters can be accommodated naturally in these models.

The idea that lepton parity could arise from the spontaneous breaking of a horizontal symmetry was first suggested, to the best of our knowledge, in [17]. Explicit models, with a horizontal U(1) symmetry and a residual Z_2 (different from lepton parity), were presented in refs. [10, 16].

The plan of this paper is as follows. In section 2, we define our notations. In section 3 we present an explicit model and its predictions for the Yukawa parameters in the quark and in the lepton sectors. We emphasize that it is not easy to accommodate the parameters of the MSW solution to the solar neutrino problem with a small mixing angle. In section 4 we investigate the consequences of the residual lepton parity on R-parity violating couplings. A summary is given and various comments are made in section 5.

2. Notations

The matter supermultiplets are denoted in the following way:

$$\begin{array}{lll} Q_i(3,2)_{+1/6}\,, & \bar{u}_i(\bar{3},1)_{-2/3}\,, & \bar{d}_i(\bar{3},1)_{+1/3}\,, \\ L_i(1,2)_{-1/2}\,, & \bar{\ell}_i(1,1)_{+1}\,, & N_i(1,1)_0\,, \\ \phi_u(1,2)_{+1/2}\,, & \phi_d(1,2)_{-1/2}\,. & \end{array} \tag{2.1}$$

The N_i supermultiplets are Standard Model singlets. Their masses are assumed to be much heavier than the electroweak breaking scale but lighter than the scale of $\mathrm{U}(1)_H$ breaking. We denote this intermediate mass scale by M. Lepton number is violated by bilinear terms in the superpotential,

$$\mu_i L_i \phi_u\,, \tag{2.2}$$

and by trilinear terms in the superpotential,

$$\lambda_{ijk} L_i L_j \bar{\ell}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k\,. \tag{2.3}$$

Baryon number is violated by trilinear terms in the superpotential,

$$\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k\,. \tag{2.4}$$

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There are also L breaking supersymmetry breaking bilinear terms in the scalar potential:

$$B_i L_i \phi_u \,, \tag{2.5}$$

and

$$\tilde{m}_{i0}^2 L_i^\dagger \phi_d \,, \tag{2.6}$$

where here L_i, ϕ_d and ϕ_u denote scalar fields.

3. The Yukawa hierarchy

3.1 A simple model

Consider a model with a horizontal symmetry $\mathrm{U}(1)_H$. The symmetry is broken by two small parameters, λ and $\bar{\lambda}$, to which we attribute H-charges of $+1$ and -1, respectively. We give them equal values (so that the corresponding D terms do not lead to supersymmetry breaking at a high scale). For concreteness we take $\lambda = \bar{\lambda} = 0.2$. At low energies, we have then the following selection rules:

(a) Terms in the superpotential and in the Kahler potential that carry an integer H-charge n are suppressed by $\mathcal{O}(\lambda^{|n|})$.

(b) Terms in the superpotential and in the Kahler potential that carry a non-integer charge vanish.

We set the H charges of the matter fields as follows:

$$\begin{array}{cc} \phi_u & \phi_d \\ (0) & (0) \end{array} \tag{3.1}$$

$$\begin{array}{ccccccccccc} Q_1 & Q_2 & Q_3 & & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 & & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 \\ (3) & (2) & (0) & & (4) & (2) & (0) & & (4) & (3) & (3) \end{array} \tag{3.2}$$

$$\begin{array}{ccccccccccc} L_1 & L_2 & L_3 & & \bar{\ell}_1 & \bar{\ell}_2 & \bar{\ell}_3 & & N_1 & N_2 & N_3 \\ (\frac{7}{2}) & (\frac{-1}{2}) & (\frac{-1}{2}) & & (\frac{11}{2}) & (\frac{11}{2}) & (\frac{7}{2}) & & (\frac{-1}{2}) & (\frac{1}{2}) & (\frac{1}{2}) \end{array} \tag{3.3}$$

The selection rules dictate then the following form for the quark mass matrices:

$$M_u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda^7 & \lambda^5 & \lambda^3 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{pmatrix}, \qquad M_d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda^7 & \lambda^6 & \lambda^6 \\ \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^4 & \lambda^3 & \lambda^3 \end{pmatrix}. \tag{3.4}$$

In eq. (3.4) and below, unknown coefficients of $\mathcal{O}(1)$ are not explicitly written. These mass matrices give order of magnitude estimates for the physical parameters (masses and mixing angles) that are consistent with the experimental data (extrapolated to a high energy scale):

$$\begin{aligned}
&\frac{m_t}{\langle\phi_u\rangle} \sim 1\,, &&\frac{m_c}{m_t} \sim \lambda^4\,, &&\frac{m_u}{m_c} \sim \lambda^3\,,\\
&\frac{m_b}{m_t} \sim \lambda^3\,, &&\frac{m_s}{m_b} \sim \lambda^2\,, &&\frac{m_d}{m_s} \sim \lambda^2\,,\\
&|V_{us}| \sim \lambda\,, &&|V_{cb}| \sim \lambda^2\,, &&|V_{ub}| \sim \lambda^3\,.
\end{aligned} \tag{3.5}$$

For the charged leptons mass matrix M_ℓ, the neutrino Dirac mass matrix $M_\nu^{\rm Dirac}$, and the Majorana mass matrix for the singlet neutrinos M_N, we have

$$M_\ell \sim \langle\phi_d\rangle \begin{pmatrix} \lambda^9 & \lambda^9 & \lambda^7 \\ \lambda^5 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^5 & \lambda^3 \end{pmatrix}\,, \tag{3.6}$$

$$\begin{aligned}
M_\nu^{\rm Dirac} &\sim \langle\phi_u\rangle \begin{pmatrix} \lambda^3 & \lambda^4 & \lambda^4 \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}\,,\\
M_N &\sim M \begin{pmatrix} \lambda & 1 & 1 \\ 1 & \lambda & \lambda \\ 1 & \lambda & \lambda \end{pmatrix}\,.
\end{aligned} \tag{3.7}$$

These matrices give the following order of magnitude estimates:

$$\begin{aligned}
&\frac{m_\tau}{\langle\phi_d\rangle} \sim \lambda^3\,, &&\frac{m_\mu}{m_\tau} \sim \lambda^2\,, &&\frac{m_e}{m_\mu} \sim \lambda^4\,,\\
&\frac{m_{\nu_3}}{(\langle\phi_u\rangle^2/M)} \sim \frac{1}{\lambda}\,, &&\frac{m_{\nu_2}}{m_{\nu_3}} \sim \lambda^2\,, &&\frac{m_{\nu_1}}{m_{\nu_2}} \sim \lambda^4\,,\\
&|V_{e\nu_2}| \sim \lambda^2\,, &&|V_{\mu\nu_3}| \sim 1\,, &&|V_{e\nu_3}| \sim \lambda^4\,.
\end{aligned} \tag{3.8}$$

The neutrino parameters fit the atmospheric neutrino data and the small mixing angle (SMA) MSW solution of the solar neutrino problem [18].

3.2 The neutrino mass hierarchy

As concerns neutrino parameters, the most predictive class of models is the one where s_{23} and $\Delta m^2_{\rm SN}/\Delta m^2_{\rm AN}$ depend only on the horizontal charges of L_2, L_3, $\bar\ell_2$ and $\bar\ell_3$ [19, 20]. We call such models, where the horizontal charges of neither the first generation nor sterile neutrinos affect the above parameters, (2,0) models. Models with n_a active and n_s sterile neutrinos are denoted by (n_a, n_s). It was proven in [21] that in $(2, n_s \le 2)$ models, for neutrinos with large mixing, $s_{23} \sim 1$, we have $m_2/m_3 \sim \lambda^{4n}$ ($\Delta m^2_{\rm SN}/\Delta m^2_{\rm AN} \sim \lambda^{8n}$). Therefore, the MSW solutions, which require $\Delta m^2_{\rm SN}/\Delta m^2_{\rm AN} \sim \lambda^2 - \lambda^4$, cannot be accommodated in this framework. The LMA solution can be achieved in $n_a = 3$ models (for any n_s) but the SMA solution requires

$n_s \geq 3$. (For an $n_s = 3$ model, see, for example, [22].) This means a loss of predictive power, particularly in comparison with $n_s = 0$ models.

The proof in ref. ([21]) referred to models with only integer horizontal charges (in units of the charge of the breaking parameters). The question arises then whether one can have a hierarchy for $\Delta m^2_{\rm SN}/\Delta m^2_{\rm AN}$ that is milder than λ^{8n} in models where leptons carry half-integer charge even for $n_s \leq 2$. We now show that the answer to this question is negative.

Consider (2,0) models with $H(L_2) \neq H(L_3)$. The large mixing can be obtained from the charged lepton mass matrix if the following condition is fulfilled [21]:

$$H(L_2) + H(L_3) = -2H(\bar{\ell}_3)\,. \tag{3.9}$$

The hierarchy is given by

$$\frac{m(\nu_2)}{m(\nu_3)} \sim \lambda^{2|H(L_2)+H(L_3)|-4|H(L_3)|}\,. \tag{3.10}$$

From (3.9) and (3.10) we find

$$\frac{\Delta m^2_{\rm SN}}{\Delta m^2_{\rm AN}} \sim \lambda^{8(|H(\bar{\ell}_3)|-|H(L_3)|)}\,. \tag{3.11}$$

Since $H(\bar{\ell}_3)$ and $H(L_3)$ are both half-integers, the difference $|H(\bar{\ell}_3)| - |H(L_3)|$ is an integer and the hierarchy is λ^{8n}.

The same statement ($\Delta m^2_{\rm SN}/\Delta m^2_{\rm AN} \sim \lambda^{8n}$) holds also in (2,2) models. (The proof for that is quite lengthy; it follows lines similar to appendix A in [21] and we do not present it here.) We conclude then that models where leptons carry half-integer charges do not provide new ways to achieve a mild hierarchy between $\Delta m^2_{\rm SN}$ and $\Delta m^2_{\rm AN}$. For the MSW solutions we have either the LMA solution with $\nu_e - \nu_\mu$ forming a pseudo-Dirac neutrino or at least three sterile neutrinos playing a role in the light neutrino flavor parameters.

4. L and B violation

The model described above has an exact Z_2 symmetry, that is lepton parity. This symmetry follows from the selection rules. But it can be understood in a more intuitive way from the full high energy theory. We assume here that our low energy effective theory given in the previous section comes from a (supersymmetric version [23] of) the Froggatt-Nielsen mechanism [24]. The full high energy theory has an exact $\mathrm{U}(1)_H$ symmetry that is spontaneously broken by the VEVs of two scalar fields, ϕ and $\bar{\phi}$, of H-charges $+1$ and -1, respectively. Quarks and leptons in vector representation of the SM gauge group and of $\mathrm{U}(1)_H$, and with very heavy masses $M_{\rm FN}$ communicate the information about the breaking to the SSM fields ($\lambda = \langle\phi\rangle/M_{\rm FN}$ and $\bar{\lambda} = \langle\bar{\phi}\rangle/M_{\rm FN}$).

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The $U(1)_H$ symmetry has a Z_2 subgroup where all fields that carry half-integer H-charges are odd, while all those that carry integer H-charges are even. This symmetry is not broken by $\langle\phi\rangle$ and $\langle\bar{\phi}\rangle$ since ϕ and $\bar{\phi}$ are Z_2 even. Our choice of H-charges is such that all leptons (L_i, $\bar{\ell}_i$ and N_i) carry half-integer charges and therefore are Z_2-odd. All other fields (quarks and Higgs fields) carry integer charges and therefore are Z_2-even. We can identify the exact residual symmetry then as lepton parity.

Lepton parity is very powerful in relaxing the phenomenological problems that arise in supersymmetric models without R_p. In particular, it forbids the bilinear μ terms of eq. (2.2), the B terms of eq. (2.5), the $\tilde{m}^2$ terms of eq. (2.6), and the trilinear terms of eq. (2.3). The only allowed renormalizable R_p violating terms are the baryon number violating couplings of eq. (2.4).

This situation has two interesting consequences:

(i) Similarly to R_p conserving models, the only allowed μ term is $\mu\phi_u\phi_d$ and the only allowed B term is $B\phi_u\phi_d$. The μ and B terms are then aligned. Furthermore, the mass-squared matrix for the scalar $(1,2)_{-1/2}$ fields can be separated to two blocks, a 3×3 block for the three slepton fields and a single term for ϕ_d. Therefore there will be no renormalizable tree-level contribution to neutrino masses [25, 3]. Consequently, the very large H charges that are needed to achieve precise μ-B alignment are not necessary here.

Since the λ_{ijk} and λ'_{ijk} couplings vanish, there will also be no R_p breaking loop contributions to neutrino masses. On the other hand, the usual see-saw contributions which break lepton number by two units are allowed. This justifies why we considered (3.7) as the only source for neutrino masses.

(ii) Since processes that violate lepton number by one unit are forbidden, the proton is stable. (We assume here that there is no fermion that is lighter than the proton and does not carry lepton number.) The most severe constraints on baryon number violating couplings are then easily satisfied.

On the other hand, the λ'' couplings of eq. (2.4) contribute to double nucleon decay, to neutron-antineutron oscillations and to other rare processes [26]–[32].

The non-observation of baryon number violating processes gives strong constraints on all the λ'' couplings, e.g.

$$\lambda''_{112} \leq 10^{-6}, \qquad \lambda''_{113} \leq 5\times 10^{-3}. \tag{4.1}$$

The first bound comes from double nucleon decay and the second from neutron-antineutron oscillations, and they correspond to a typical supersymmetric mass $\tilde{m}\sim 300\ GeV$. In our models, all the relevant constraints are satisfied since the

λ'' couplings are suppressed by the selection rules related to the broken U(1). Explicitly, our choice of H-charges in eq. (3.2) leads to the following order of magnitude estimates:

$$\begin{aligned} \lambda''_{112} \sim \lambda''_{113} \sim \lambda^{11}\,, &\qquad \lambda''_{123} \sim \lambda^{10}\,, \\ \lambda''_{212} \sim \lambda''_{213} \sim \lambda^{9}\,, &\qquad \lambda''_{223} \sim \lambda^{8}\,, \\ \lambda''_{312} \sim \lambda''_{313} \sim \lambda^{7}\,, &\qquad \lambda''_{323} \sim \lambda^{6}\,. \end{aligned} \tag{4.2}$$

The value that is closest to the bound is that of λ''_{112}, predicting double nucleon decay at a rate that, for $\tilde{m} \sim 100\ GeV$, is four orders of magnitude below the present bound.

Note, however, that reasonable variations on our model can easily give larger λ'' couplings and allow the upper bound on double nucleon decay to be saturated. For example, replacing the H charges in eq. (3.2) with a linear combination of H and baryon number B ($H' = a_1 H + a_2 B$) does not affect the B conserving quantities and, in particular, the mass matrices (3.4), (3.6) and (3.7), but does affect (and, in particular, can enhance) the λ'' couplings in (4.2). The couplings could also be affected by $\tan\beta$. Our choice of charges corresponds to $\tan\beta \sim 1$. But for large $\tan\beta$ and the same choice of H-charges for ϕ_d and Q_i, the λ'' couplings are enhanced by $\tan^2\beta$. We conclude that, within our framework, baryon number violating processes could occur at observable rates.

5. Summary and comments

In the framework of supersymmetric models, horizontal U(1) symmetries can lead to many interesting consequences, the most important being a natural explanation of the smallness and hierarchy in the Yukawa parameters. We have investigated a particular class of models, where the horizontal U(1) is the *only* symmetry imposed on the model beyond supersymmetry and the Standard Model gauge symmetry. In particular, we have imposed neither R-parity, nor lepton number nor baryon number. Usually, such models can be made viable only at the price of assigning uncomfortably large horizontal charges to various matter fields. It is possible, however, that the horizontal symmetry leads to exact lepton parity at low energy. The constraints that usually require the large charges are irrelevant because proton decay is forbidden and because mixing between neutrinos and neutralinos is forbidden. The remaining constraints from double nucleon decay and from neutrino masses are easily satisfied by the selection rules of the broken U(1).

Our emphasis here has been put on lepton and baryon number violation. Therefore, we have ignored two other aspects of our framework. First, we did not insist that the horizontal symmetry solves the supersymmetric flavor problem. It is actually impossible to sufficiently suppress the supersymmetric contributions to flavor changing neutral currents by means of a single horizontal U(1) symmetry. It is possible that this problem is solved by a different mechanism. For example, squarks and sleptons could be degenerate as a result of either dilaton dominance in Supersymmetry breaking or a universal gaugino contribution in the RGE (for a recent discussion, see [33]). Alternatively, one could complicate the model by employing a U(1) × U(1) symmetry to achieve alignment [34, 35]. In either case, the implications for the issues discussed here do not change.

We note, however, that we cannot embed our models in the framework of gauge mediated Supersymmetry breaking (GMSB) [36]–[39] with a low breaking scale. The reason is that such models predict that the gravitino is lighter than the proton. If baryon number is not conserved, the proton decays via $p \to G + K^+$. The λ''_{112} coupling contributes to this decay at tree level and is therefore very strongly constrained [40, 32]:

$$\lambda''_{112} \leq 5 \times 10^{-16} \left(\frac{\tilde{m}}{300\ GeV}\right)^2 \left(\frac{m_{3/2}}{1\ eV}\right). \tag{5.1}$$

All other λ''_{ijk} couplings contribute at the loop level and are constrained as well [41]. For $m_{3/2} \sim 1\ eV$, the bound (5.1) would be violated (with $\lambda''_{112} \sim \lambda^{11}$) by about eight orders of magnitude. Therefore, our models of horizontal U(1) symmetry broken to lepton parity can be embedded in the GMSB framework only for $m_{3/2} \gtrsim 10^8\ eV$, that is a Supersymmetry breaking scale that is higher than $\mathcal{O}(10^8\ GeV)$.

Second, we have not worried about anomaly constraints [17]. The reason is that these could be satisfied by extending the matter content of the model and this, again, would have no effect on the problems of interest to us here.

In the single explicit model that we presented in section 3, our choice of lepton charges has been dictated by the implications from the atmospheric neutrino anomaly and from the MSW solution of the solar neutrino problem with a small mixing angle. We emphasize that it is actually simpler to accommodate the large angle solutions (MSW or vacuum oscillations) of the solar neutrino problem. We used the small angle option because we wanted to demonstrate that, first, it can be accommodated in our framework but that, second, the model does not offer a simplification in this regard compared to models with integer charges. The use of half-integer charges in the lepton sector also does not make significant changes for models using holomorphic zeros to achieve simultaneously large mixing and large hierarchy [20]. Finally, we note that models where some of the L_i and $\bar{\ell}_i$ carry half-integer charges and other integer charges do not yield acceptable phenomenology.

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