R-parity breaking and the grand unification program

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We present the study of the possibility to have R-parity breaking interactions in minimal SU(5). An interesting scenario emerges in which the R-parity breaking coupling $\lambda'_{333}$ is large, and its size is related to the value of the tau neutrino mass, assuming that supersymmetry is broken according to low energy supergravity framework. This scenario may also have implications on the issue of $b-\tau$ unification.

1. Spectrum of minimal SU(5)

The three gauge couplings constants of the Standard Model (SM), extrapolated assuming the existence of supersymmetric partners around the SU(2)$\times$U(1) breaking scale, are consistent with the hypothesis of SU(5) grand unification taking place at energies $E = \mathcal{O}(10^{16})$ GeV.

The matter and the Higgs fields can be arranged in supermultiplets, with the usual gauge quantum number: $\bar{5}_i$ and $10_i$ for the matter, where $i = 1, 2, 3$ refers to the family replica; $5_H$ and $\bar{5}_H$ for the Higgs field giving mass to the ordinary fermions; $24_H$ for the Higgs field that breaks SU(5) (the Higgs sector being the less certain from both the experimental and theoretical point of view).

The Higgs 5-plets, beside the usual Higgs doublets, contain triplets that are not part of the SM spectrum, whose exchange can mediate proton decay with strength of the order of the Yukawa couplings. The usual solution of this phenomenological impasse is to assume that the triplets have a mass of the order of SU(5) breaking scale, whereas the doublets have mass of the order of SU(2) breaking scale (doublet-triplet splitting).

2. R-parity violating couplings

Since the Higgs fields $5_H$ is in the same gauge group representation of the matter fields $\bar{5}_i$, beside the mass terms $5_H\bar{5}_i10_j$, and beside $\bar{5}_H5_H + 5_H24_H5_H$, giving rise to the $\mu$-term, we can write the gauge group invariants [1-3,6-8] that break explicitely R-parity (or equivalently matter parity):

$$\Lambda_{ijk}\bar{5}_i\bar{5}_j10_k$$

$$+ \bar{5}_i(M_i + h_i24_H)5_H$$

(1)

The terms in the two lines are quite different in character. We will refer to them as “trilinear matter couplings” and “matter-higgs mixings” respectively. Henceforth we will think of the bracketed term as a single effective term, since, regarding phenomenological implications, the role of the $24_H$ is just to communicate the SU(5) breaking.

2.1. Trilinear matter couplings

If the first term in (1) is dominating, we deduce that lepton- and baryon-number violating interactions are induced with the same strength. Supersymmetric partners of quark fields can in this case mediate proton decay, and therefore the size of the couplings $\Lambda_{ijk}$ is strongly limited in size from the available informations on proton stability: $\Lambda_{ijk} < \mathcal{O}(10^{-9})$. Such a small couplings are not interesting for experimental search at accelerators.

The key hypothesis that forces this conclusion is the quark-lepton symmetry, which implies that baryon- and lepton-violations appear at the same time. Therefore, a conjectural observation of large R-parity breaking couplings should be related to asymmetries between quarks and leptons. In the next section we illustrate how such an asymmetry can arise in the simple model at hand.
2.2. Matter-higgs mixings

The asymmetry between quarks and leptons can be related to the doublet-triplet splitting. In fact, after the SU(5) breaking has taken place, the second term in eq. (4) can be written together with the R-parity conserving analogue as follows:

\[
(B^c, L_3) \left( \begin{array}{cc} m_T & 0 \\ 0 & m_0 \end{array} \right) \left( \begin{array}{c} T \\ H_2 \end{array} \right) + (T^c, H_1) \left( \begin{array}{cc} M_T & 0 \\ 0 & M_0 \end{array} \right) \left( \begin{array}{c} T \\ H_2 \end{array} \right),
\]

where we retained the mixing terms of the higgs with third generation matter fields, and introduced four effective masses for triplet and doublet subspaces (we assume that, consistently with previous discussion, the trilinear matter couplings are negligible). It is possible to redefine as superfield triplet \(T^c\) and as doublet \(H_1\) the combinations:

\[
m_T B^c + M_T T^c \rightarrow \mu_T T^c \\
m_0 L_3 + M_0 H_1 \rightarrow \mu_0 H_1,
\]

but this redefinition (called “matter-higgs rotation”) will modify other terms in the lagrangian. In particular, an R-parity violating coupling of the \(L_3Q_3B^c\) monomial will be generated out of the bottom Yukawa term \(H_1Q_3B^c\) with strength:

\[
\lambda_{333} \sim y_b \theta_0,
\]

where \(\theta_0\) is the matter-higgs mixing angle and \(y_b\) the bottom Yukawa coupling. Under the assumption that \(M_T\) is of the order of the SU(5) breaking scale and the other masses are of the order of the electroweak scale (a generalization of the doublet-triplet splitting hypothesis), the baryon-violating couplings are small and do not conflict with proton stability. At the same time we can have values of \(\lambda_{333}\) coupling interesting for search at accelerators.

One phenomenological and one theoretical remarks are in order. Let us notice that hadronic jets originating from a vertex \(\lambda_{333}\) are enriched in bottom quarks; furthermore, if the angle \(\theta_0\) is small enough, the decay of the lighter supersymmetric particles will be slow and originate secondary vertices. The other remark is that the bottom mass is smaller than the tau Yukawa mass at the unification scale after the matter-higgs rotation. This can be rephrased by saying that the matter-higgs rotation breaks the SU(4) residual symmetry associated to the 5-plet breaking pattern. A second possible effect on \(b-\tau\) unification is discussed below.

The matter-higgs rotation has in general important effects also on the scalar sector of the theory [1,3-8]. To discuss this point properly one must assume a framework for supersymmetry breaking. We consider here the low-energy supergravity model, that, implying universality, guarantees the absence of large flavour-changing neutral currents. Let us write the part of the scalar potential that contains the Higgs doublet \(h_1\) and the slepton doublet \(\tilde{l}_3\) in the following manner:

\[
V \equiv (m_{L_3}^2 + \delta m^2) |h_1|^2 + m_{L_3}^2 |\tilde{l}_3|^2 - [B \cdot M_0 \cdot h_1 h_2 + (\tilde{B} + \delta B) \cdot m_0 \cdot \tilde{l}_3 h_2 + \text{h.c.}].
\]

At the grand unification (or Planck) scale we have:

\[
\delta B(M_X) = 0 \\
\delta m^2(M_X) = 0,
\]

as a consequence of supergravity. Were this be true at all the scales, the matter-higgs rotation would be harmless in the scalar sector. However, non-zero values of \(\delta B\) and \(\delta m^2\) will be induced by \(\mathcal{O}(\langle y_0^2 \rangle)\) renormalization group effects [1,6-8]. [It is convenient to study the running before the matter-higgs rotation is performed, since in this basis the massive terms that break R-parity do not modify the evolution of the other terms.] For this reason the potential in the rotated basis will contain after SU(2)×U(1) breaking the terms:

\[
V_L \sim \theta_0 \times [\delta m^2 h_1^* + (B + \mu) \cdot h_2] \tilde{l}_3 + \text{h.c.},
\]

implying a breaking of the tau lepton number. The sneutrino vacuum expectation value can be estimated as:

\[
\langle \tilde{\nu}_3 \rangle \sim v \theta_0 y_b^2,
\]

barring the possibility of cancellations among various contributions. As a consequence of the sneutrino VEV, the tau neutrino mixes with the zino, and become massive. Equations (4) and (8) im-
ply a correlation between the R-parity breaking couplings and the tau neutrino mass:
\[
\lambda'_{333} \sim 0.001 \times \left[ \frac{\theta_D}{0.1 \text{ rad.}} \right]^{1/2} \times \left[ \frac{m_{\nu}}{30 \text{ eV}} \right]^{1/4} \times \left[ \frac{M_{\tilde{Z}}}{1 \text{ TeV}} \right]^{1/4}.
\]

that, with a tau neutrino in an interesting range for cosmological considerations, does not preclude the discovery at accelerators of R-parity breaking effects. [The domain of validity of formula (9) is limited by the perturbativity of the Yukawa couplings, its accuracy depending mainly on the measured value of the bottom mass and on the estimation (8).]

Finally we comment on the scenario in which the tau neutrino mass is large, \(\mathcal{O}(\text{MeV})\). This possibility is related to the fact that the parameter \(\theta_D\) is arbitrary, and can thus be chosen to saturate the experimental bound. Among the consequences of this assumption we remark the following: (i) Of course \(m_{\nu_e}\) may be measured in \(\tau\) decay experiments. (ii) Such a heavy neutrino should be unstable to avoid cosmological bounds. [A proper discussion of this issue would requires to quantify the mixing with the other neutrinos, and will not be addressed here.] (iii) Regarding search at accelerators, it is important to remark that the correlation (9) does not affect dramatically the size of the R-parity breaking coupling. (iv) In the optimistic case in which the effects of \(\lambda'_{333}\) would show up at accelerators, the model described above for the neutrino mass should be considered as an alternative to the see-saw model. (v) The vacuum expectation value (8), combining with the R-parity breaking coupling (9), will give a contribution to the bottom mass of the order \(\delta m_b \sim m_b (\theta_D y_b)^2\) (its actual size and sign depending on the values of the supersymmetric parameters), that may be relevant for \(b - \tau\) unification. This is larger than the \(\mathcal{O}(\theta_D^2)\) contribution from matter-higgs rotation if \(\tan \beta = \langle h_0^0 \rangle / \langle h_1^0 \rangle\) is large.

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1. The results exposèd in this talk are mainly based on the paper: “Large R parity violating couplings and grand unification”, A.Yu. Smirnov and F. Vissani, Nucl.Phys. B 460, 37 (1996) to which we refer for details and more complete bibliography. Early works investigating R-parity in the grand unification context are [2-4]; the attention on this subject has been recently renewed by [5-10]. Related studies on R-parity breaking can be found in the contributions of H. Baer, V. Barger, G. Bhattacharyya, H. Klapdor-Kleingrothaus, N. Polonsky and Y. Siros.

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