

European Network on Physics beyond the Standard Model, 1999

Yukawa couplings and proton decay in SUSY models

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ABSTRACT: We discuss proton decay induced by dimension-5 operators in supersymmetric models containing extra hypercharge-1/3 colour-triplets. We derive a general formula relating dimension-5 operator to the colour-triplet mass matrix. We show that certain zeros in the triplet mass-matrix together with some triplet coupling selection rules can lead to elimination of dimension-5 operators. We apply this mechanism to $SU(5)$ and flipped $SU(5)$ theories with extended Higgs sectors.

Contents

1. Introduction

Proton decay is a generic feature of any unification scheme since the unification of quarks and leptons in a common multiplet introduces extra interactions that violate baryon number. Proton decay rates and modes are a prediction of GUT models that play a crucial role in their phenomenological viability. In fact, proton decay has turned out to be the nemesis of many GUT and Superstring models. It is a welcome prediction that can be used to test GUTs. In supersymmetric GUTs with conserved R -parity the dominant baryon number violating operators are dimension $D = 5$, while $D = 6$ operators are in general suppressed due to the increase of the unification scale in comparison to its non-supersymmetric values. $D = 5$ operators are proportional to the Yukawa couplings and to the inverse of the heavy mass [1]. In minimal models the Yukawa couplings involved are associated with the fermion masses. The values of these couplings play an important role in the final value of the proton decay rate and the resulting hierarchy of existing modes. Nevertheless, Superstring embeddable models [2] or models of phenomenologically oriented GUTs that treat the fermion mass problem [3], come out with an extended Higgs sector.

In this talk we summarize the results of a recent work [4], where we propose a mechanism for eliminating or suppressing such operators based on the use of textures of the hypercharge $1/3$ mass-matrix accompanied by certain constraints of the extra triplet coupling to matter.

2. Proton Decay in minimal $SU(5)$ models

Let us consider unified models with the minimal Higgs content to allow the breaking of the $SU(5)$ symmetry to $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the GUT scale M_{GUT} .

Non Supersymmetric $SU(5)$ models predict proton decay as a consequence of gauge interactions of the heavy particles, originated when the $SU(5)$ symmetry is broken, and quarks and leptons. The baryon-number-violating operators are $D = 6$ and they are suppressed as the square of the mass of the heavy particles ($\approx M_{GUT}$). The dominant proton decay mode in these models is $p \rightarrow e^+ \pi^0$. The calculated lifetime [5] is :

$$\tau(p \rightarrow e^+ \pi^0) \approx \left(\frac{M_{GUT}}{3.5 \cdot 10^4 \text{GeV}} \right)^4 \times 10^{31 \pm 1} \text{yr} \quad (2.1)$$

While the experimental bound for this process is [6]

$$\tau(p \rightarrow e^+\pi^0) > 5.5 \times 10^{32} \text{years}$$

Since typical values for the *cuasi* unification in non-susy $SU(3)_c \times SU(2)_L \times U(1)_Y$ are $M_{GUT} \approx 10^{13} - 10^{14} \text{Gev}$, proton lifetime predictions exceeds the experimental bounds.

In SUSY $SU(5)$ models, the scale of unification is increased to $M_{GUT} \approx 10^{16} \text{Gev}$, this is enough to bring the prediction for $D = 6$ mediated proton decay to a safe limit:

$$\tau(p \rightarrow e^+\pi^0) \approx 10^{35 \pm 1} \text{years}$$

However proton decay is predicted, at smaller rates, due to Yukawa interactions. In this case the supersymmetric partners of the colored triplet Higgs bosons interact with leptons (sleptons) and quarks (squarks) fields. $D = 5$ operators arises suppressed only by one power of M_{GUT} .

Color triplets are contained in Higgs pentaplets h, \bar{h} . The quarks and leptons are assigned to $\phi(\mathbf{5}) + \psi(\mathbf{10})$ representations of $SU(5)$. The part of the superpotential related to dimension-5 decay will be

$$Y_{ij}^u \psi_i \psi_j h_1 + Y_{ij}^d \psi_i \phi_j \bar{h}_1 + \mu h \bar{h} + \lambda h \Sigma \bar{h} , \quad (2.2)$$

where the symbol Σ stands for the adjoint Higgs superfield in the **24** representation.

The $SU(5)$ symmetry is broken down to the MSSM, when Σ gets a VEV, V , along the 24-direction. The isodoublet and colour-triplet masses are

$$M_2 = \mu - 3\lambda V , \quad (2.3)$$

$$M_3 = \mu + 2\lambda V \quad (2.4)$$

The triplets are heavy, $M_3 \sim M_{GUT}$, while the doublet pair must remain light $M_2 \sim m_w$. Hence a fine-tuning condition must be imposed in the parameters of the superpotential (2.2).

The effective $SU(3)_c \times SU(2)_L \times U(1)_Y$ superpotential describing the couplings of quarks and leptons to the extra coloured triplets of the D -quark type

$$Y_{ij}^u Q_i Q_j D + Y_{ij}^d Q_i L_j \bar{D} + Y_{ij}^u E_i^c U_j^c D , \quad (2.5)$$

$D = 5$ operators can be converted into four-fermion operators by the appropriate gaugino dressing. Assuming roughly an overall universal supersymmetry breaking scale m_S , the corresponding four-fermion operator will involve:

$$\lambda \cdot \left[\frac{(M_3)^{-1}}{m_S} - 4m_S (M_3)^{-3} \log \frac{(M_3)}{m_S} \right] \quad (2.6)$$

Where λ contain a combination of Yukawa and gauge couplings.

The theoretical predictions [5] for the mode $p \rightarrow \bar{\nu} K$ are comparable to the experimental bound for this mode [6]

$$\tau(p \rightarrow \bar{\nu}K) > 5.5 \times 10^{32} \text{yr.}$$

Hence, the parameter space for the minimal SUSY– $SU(5)$ is very restricted.

In $SU(5)$ –models with a non-minimal content of Higgs multiplets, M_3^{-1} of eq. (2.6) will be replaced by a matrix, and therefore its null elements will play an important role in the suppression of $D = 5$ –operator mediated proton decay.

In the minimal flipped $SU(5) \times U(1)$ model [7] matter fields come in the representations

$$F_i(\mathbf{10}, 1/2) , \quad f_i^c(\bar{\mathbf{5}}, -3/2) , \quad l_i^c(\mathbf{1}, 5/2) \quad (2.7)$$

while Higgses in

$$h(\mathbf{5}, -1) , \quad \bar{h}(\bar{\mathbf{5}}, 1) , \quad (2.8)$$

and in

$$F_h(\mathbf{10}, 1/2) , \quad \bar{F}_h(\bar{\mathbf{10}}, -1/2) . \quad (2.9)$$

The part of the superpotential relevant for the breaking of the unifying symmetry and Yukawa terms is:

$$\begin{aligned} & f_{ij}F_i F_j h + y_{ij}F_i f_j^c \bar{h} + r_{ij}l_i^c f_j^c \bar{h} + \\ & \mu_h \bar{h} + \lambda F_h F_h h + \overline{\lambda} \bar{F}_h \bar{F}_h \bar{h} \end{aligned} \quad (2.10)$$

VEV’s of F_h and \bar{F}_h along the neutrino-like component break the $SU(5) \times U(1)$ symmetry to the MSSM. A great advantage of the “flipped” $SU(5)$ model over the ordinary one is that of the realization of the “triplet–doublet splitting” mechanism without fine–tuning the parameters of the superpotential (2.10). In this case the doublet mass is given by the parameter μ which can be $\sim m_w$ while the mass matrices for the triplets:

$$\mathcal{M}_3 = \begin{pmatrix} 0 & \lambda V \\ \overline{\lambda} \overline{V} & 0 \end{pmatrix} \quad (2.11)$$

Where the entry 22 is null since the pair $F_h \bar{F}_h$ has to be massless in order to realize the $SU(5) \times U(1)$ breaking to the standard model. Since in this model there is not $D\bar{D}$ mass term, $D = 5$ –operators are naturally suppressed.

3. How to suppress dimension–5 operators in effective models with extra triplets

Let us consider a general supersymmetric model containing some extra hypercharge– $1/3$ colour–triplets¹. The effective $SU(3)_c \times SU(2)_L \times U(1)_Y$ superpotential describing

¹This superpotential arises in the case of the standard $SU(5)$ with extra Higgs 5–plets or from the flipped $SU(5) \times U(1)$ with both extra Higgs 5–plets and 10–plets.

the couplings of quarks and leptons to the extra coloured triplets of the D -quark type

$$f_{ij}^\alpha Q_i Q_j D_\alpha + y_{ij}^\alpha Q_i L_j \bar{D}_\alpha + r_{ij}^\alpha E_i^c U_j^c \bar{D}_\alpha , \quad (3.1)$$

where $i, j = 1, 2, 3$ are the usual generation indices and $\alpha = 1, \dots, N$ is an extra index describing the multiplicity of triplets and repeated indices are summed. In addition the effective triplet mass matrix will be of the form

$$(\mathcal{M}_3)_{\alpha\beta} D_\alpha \bar{D}_\beta \quad (3.2)$$

where \mathcal{M}_3 is in general non-diagonal.

We can always go to a basis in which the triplet mass-matrix is diagonal

$$D_\alpha = S_{\alpha\beta} D'_\beta , \quad \bar{D}_\alpha = U_{\alpha\beta} \bar{D}'_\beta \quad (3.3)$$

$$\mathcal{M}_{3D} \equiv \text{diag}(m_1, m_2, \dots, m_N) = S^T \mathcal{M}_3 U \quad (3.4)$$

where the matrices S and U are unitary. In this basis we can easily evaluate $D = 5$ operators resulting from Higgs triplet fermion exchange, and then recast the result in the original basis. Assuming that all triplets are massive ($m_i \neq 0, i = 1, \dots, N$), operators with the structure $Q_i Q_j Q_k L_n$ will be proportional to ²

$$\begin{aligned} \mathcal{O}_{ijkl}^{QQQL} &= \sum_{\alpha, \beta, \gamma=1}^N f_{ij}^\alpha S_{\alpha\gamma} (\mathcal{M}_{3D}^{-1})_{\gamma} U_{\beta\gamma} y_{kn}^\beta \\ &= \sum_{\alpha, \beta=1}^N f_{ij}^\alpha (\mathcal{M}_3^{-1})_{\alpha\beta}^T y_{kn}^\beta \\ &= \frac{1}{\det(\mathcal{M}_3)} \sum_{\alpha, \beta=1}^N f_{ij}^\alpha \text{cof}(\mathcal{M}_3)_{\alpha\beta} y_{kn}^\beta \end{aligned} \quad (3.5)$$

Analogous formulas hold for $D = 5$ operators of the type $Q_i Q_j U_k^c E_k^c$.

Suppose now that we want to eliminate all dimension five operators. Assuming that the Yukawa couplings f_{ij}^α and y_{ij}^β are in general unrelated and $\det \mathcal{M}_3 \neq 0$, equation (3.5) implies that *the necessary and sufficient condition for vanishing of the $\mathcal{O}_{ijkl}^{QQQL}$ operator is that for every pair of triplets (D^α, \bar{D}^β , $\alpha, \beta = 1, \dots, N$) that do couple to quarks and leptons respectively ($f_{ij}^\alpha \neq 0$ and $h_{ij}^\beta \neq 0$) the cofactor of the corresponding triplet mass matrix element $(\mathcal{M}_3)_{\alpha\beta}$ vanishes³*

$$\begin{aligned} \mathcal{O}_{ijkl}^{QQQL} = 0 &\iff \text{cof}(\mathcal{M}_3)_{\alpha\beta} = 0 \\ \forall (\alpha, \beta) \in \Xi &= \{(\alpha, \beta) : f_{ij}^\alpha \neq 0 \\ &\text{and } h_{kl}^\beta \neq 0\} . \end{aligned} \quad (3.6)$$

²The corresponding four-fermion operator, assuming roughly an overall universal supersymmetry breaking scale m_S , will involve $\frac{(\mathcal{M}_3)^{-1}}{m_S} - 4m_S(\mathcal{M}_3)^{-3} \log \frac{(\mathcal{M}_3)}{m_S}$.

³We consider here the triplet D^α as coupled to quarks and leptons if at least one $f_{ij}^\alpha \neq 0$ and similarly for anti-triplets.

It is obvious that in the case where all triplets (D 's and \bar{D} 's) couple to matter the suppression of dimension five operators (3.5) is not possible since (3.6) leads to $\det(M_3) = 0$. Nevertheless, if for some reason (discrete symmetry, R-parity, anomalous $U(1)$, accidental symmetry) some of the f_{ij}^α and/or y_{kl}^β are zero and the triplet mass matrix is such that the cofactors of the appropriate matrix elements are zero then the associated dimension-5 operator vanishes.

The previous discussion leads to the possibility that *in a model with extra D -quark triplets dimension-5 operators can be eliminated by using textures of triplet mass matrices and the triplet-matter couplings.*

To be concrete let us give a simple example of such an effective theory. Consider the case of an effective theory with two extra triplets. Only the first couples to matter through the superpotential terms

$$f_{ij}^1 Q_i Q_j D_1 + y_{ij}^1 Q_i L_j \bar{D}_1 + r_{ij}^1 E_i^c U_j^c \bar{D}_1 \quad (3.7)$$

and their mass-matrix has the form

$$\mathcal{M}_3 = \begin{pmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & 0 \end{pmatrix}. \quad (3.8)$$

Since $f_{ij}^2 = y_{ij}^2 = 0$ evaluation of (3.5) leads to

$$\mathcal{O}_{ijkl}^{QQQL} = f_{ij}^1 \text{cof}(\mathcal{M}_3)_{11} y_{kn}^1 \sim \text{cof}(\mathcal{M}_3)_{11} = 0 \quad (3.9)$$

It is remarkable that if we remove the second pair of triplets of the model (which do not couple directly to matter) the usual dimension-5 operators reappear. We shall study below that this nice property can be incorporated in $SU(5)$ models.

4. $SU(5)$ models without dimension-5 operators

Let us consider now an $SU(5)$ model with two pairs of Higgs pentaplets $h_\alpha, \bar{h}_\alpha, \alpha = 1, 2$ of which only the first couples to matter. The quarks and leptons are assigned to $\phi(\mathbf{5}) + \psi(\mathbf{10})$ representations of $SU(5)$. The part of the superpotential related to dimension-5 decay will be

$$f_{ij} \psi_i \psi_j h_1 + y_{ij} \psi_i \phi_j \bar{h}_1 + \sum_{\alpha, \beta=1}^2 (\mu_{\alpha\beta} h_\alpha \bar{h}_\beta + \lambda_{\alpha\beta} h_\alpha \Sigma \bar{h}_\beta), \quad (4.1)$$

where the symbol Σ stands for the adjoint Higgs superfield in the $\mathbf{24}$ representation. The isodoublet and colour-triplet mass matrices are correspondingly of the form

$$\mathcal{M}_2 = \mu - 3\lambda V, \quad (4.2)$$

$$\mathcal{M}_3 = \mu + 2\lambda V \quad (4.3)$$

The well known fine-tuning that guarantees a massless pair of isodoublets amounts to

$$\det(\mathcal{M}_2) = 0 . \quad (4.4)$$

The proton decay rate through $D = 5$ operators is, according to equation (3.5), determined by the cofactor of the 1 – 1 element of the triplet mass matrix

$$\text{cof}(\mathcal{M}_3)_{11} = (\mu_{22} + 2\lambda_{22}V) . \quad (4.5)$$

Hence, choosing $\mu_{22} = -2\lambda_{22}V$ dimension-5 operators vanish. This condition is perfectly compatible with the previous fine-tuning condition (4.4). It is very interesting that proton decay through $D = 5$ operators can be set to zero through a condition on the couplings ⁴.

In the framework of our standard $SU(5)$ example the required zero in the inverse triplet mass matrix does not correspond to any symmetry and is in a sense a second fine-tuning. Nevertheless, the general conclusion is that zeros of the triplet mass matrix, perhaps attributable to symmetries, can stabilize the proton.

The superpotential considered above in (4.1) is not the most general one. In fact, the case that all 5-plets couple to matter cannot be reduced to (4.1) since it would require a different Higgs 5-plet rotation for each generation of matter. However, we should emphasize the fact that in $SU(5)$ models with non minimal Higgs content, the constraints imposed by proton decay on the parameter space and triplet masses can be relaxed.

5. Dimension-5 operators in extensions of the flipped $SU(5)$

In spite of the nice features of the minimal flipped $SU(5)$ model, all attempts to obtain such a model from strings have yielded up to now non-minimal models. Such models include

- (a) extra pairs of low energy Higgses (h, \bar{h}) and/or
- (b) extra pairs of $SU(5) \times U(1)$ breaking Higgses (F_h, \bar{F}_h).

We are thus motivated to study the presence of dimension-5 operators in such models. As we shall see contrary to the minimal case, such extensions of the flipped $SU(5)$ model are not automatically free of dimension-5 operators.

The relevant part of the superpotential assuming N_5 pairs of Higgs 5-plets ($h_\alpha, \bar{h}_\alpha, \alpha = 1, \dots, N_5$) that couple to matter and N_{10} pairs of Higgs 10-plets ($F_{hA}, \bar{F}_{hA}, A = 1, \dots, N_{10}$) that do not couple to matter, will have the form

$$\begin{aligned} & f_{ij}^\alpha F_i F_j h_\alpha + y_{ij}^\alpha F_i f_j^c \bar{h}_\alpha + \\ & r_{ij}^\alpha l_i^c f_j^c \bar{h}_\alpha + \mu_{\alpha\beta} h_\alpha \bar{h}_\beta + m_{AB} F_{hA} \bar{F}_{hB} \\ & + \lambda_{AB\gamma} F_{hA} F_{hB} h_\gamma + \bar{\lambda}_{AB\gamma} \bar{F}_{hA} \bar{F}_{hB} \bar{h}_\gamma \end{aligned} \quad (5.1)$$

⁴Of course, proton decay still goes through at the (suppressed) rate of $D = 6$ operators.

where $A, B = 1, \dots, N_{10}$, $\alpha, \beta, \gamma = 1, \dots, N_5$. Assuming GUT symmetry breaking to an arbitrary direction in the Higgs 10-plet space $((V_1, V_2, \dots, V_{N_{10}})$ and similarly for bars)⁵, we obtain the triplet mass matrix⁶

$$\mathcal{M}_3 = \begin{pmatrix} \mu_{\alpha\beta} & v_{\alpha A} \\ \bar{v}_{A\beta} & m_{AB} \end{pmatrix} \quad (5.2)$$

where $\mu_{\alpha\beta}$ is the doublet mass-matrix and $v_{\alpha A} = 2\lambda_{AB\alpha}V_B$, $\bar{v}_{A\beta} = 2\bar{\lambda}_{AB\beta}\bar{V}_B$

F-flatness demands $\det(m) = 0$ in order to have at least one pair of massless Higgs decuplets which will realize the GUT symmetry breaking. One can actually choose m to have only one zero eigenvalue so that all remnants of the Higgs decuplets will become heavy.

Let us now start our study by a simple example. Consider the flipped model with two pairs of Higgs 5-plets and one pair of Higgs 10-plets. Assuming for simplicity that the 5-plet mass matrix is diagonal, the explicit form of the triplet matrix is⁷

$$\mathcal{M}_3 = \begin{pmatrix} 0 & 0 & \lambda_1 V \\ 0 & \mu & \lambda_2 V \\ \bar{\lambda}_1 \bar{V} & \bar{\lambda}_2 \bar{V} & 0 \end{pmatrix} \quad (5.3)$$

and $\det(\mathcal{M}_3) = \lambda_1 \bar{\lambda}_1 \bar{V}$ The transpose of inverse triplet matrix entering in formula (3.5) is

$$(\mathcal{M}_3^{-1})^T = \begin{pmatrix} \frac{\lambda_2 \bar{\lambda}_2}{\lambda_1 \lambda_1 \mu} & -\frac{\lambda_2}{\lambda_1 \mu} & \cdot \\ -\frac{\lambda_2}{\bar{\lambda}_1 \mu} & \frac{1}{\mu} & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \quad (5.4)$$

where the dots stand for elements which are irrelevant. It is now obvious that in this model dimension five operators cannot be eliminated since even in the case $\bar{\lambda}_2 = \lambda_2 = 0$ the 22 element does not vanish. If we want to eliminate them we have two solutions :
(i) assume that the extra pair of 5-plets does not couple to matter. In this case only the 11 element of the matrix in (5.4) is relevant and it vanishes for $\lambda_2 = 0$ (or $\bar{\lambda}_2 = 0$).
(ii) make the milder assumption that one of the 5-plets (e.g. h_2) does not couple to the up quarks (or similarly \bar{h}_2 does not couple to the down). In this case the second column (or line) of the matrix in (5.4) becomes irrelevant and the column (or line) left vanishes for $\lambda_2 = 0$ (or $\bar{\lambda}_2 = 0$).

Another case that could arise is the existence of extra decuplets. The simplest of these cases is for $N_5 = 1$ and $N_{10} = n \geq 2$.

$$\text{cof}(\mathcal{M}_3)_{11} = \frac{\det m}{\det \mathcal{M}_3} \quad (5.5)$$

⁵D-flatness requires $\sum_A V_A^2 = \sum_A \bar{V}_A^2$

⁶In a $(D_1, \dots, D_{N_5}, (d_H^c)_1, \dots, (d_H^c)_{N_{10}})$ versus $(\bar{D}_1, \dots, \bar{D}_{N_5}, (\bar{d}_H^c)_1, \dots, (\bar{d}_H^c)_{N_{10}})$ basis, where with D we denote the triplets which lie inside the Higgs 5-plets and with D_H the triplets that lie inside the Higgs 10-plets.

⁷We have renamed $\lambda_1 = \lambda_{111}$, $\lambda_2 = \lambda_{112}$.

which means that proton decay is absent only in the case that the restricted mass-matrix of the triplets not coupled to matter has

$$\det m = 0 \tag{5.6}$$

This constrain naturally arises in the context of the flipped $SU(5) \times U(1)$ model as consequence of F-flatness as we mentoned above.

In the more general case where N_5 and N_{10} are arbitrary dimension-5 operators can be suppressed only in the case $N_5 \leq N_{10}$. Furthermore one has to require that the Higgs decuplet mass matrix has N_5 zero eigenvalues. This is compatible with symmetry breaking and with the requirement of making all triplets heavy but leaves $N_5 - 1$ pairs of $Q(\mathbf{3}, \mathbf{2}, 1/6) + \bar{Q}(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$ massless. This feature does not necessarily mean that this possibility is ruled out. On the contrary one can consider the cases where extra Q 's have intermediate masses which are small enough to sufficiently suppress dimension-5 operators but they are still compatible with renormalization group requirements. The appearance of extra vector-like pairs of Q and D type multiplets with intermediate masses is a welcomed feature in the context of flipped $SU(5) \times U(1)$ models that raise the unification scale to the string scale [8].

6. Conclusions

Our main result is that textured zeros of the color-triplet mass-matrix as well as Yukawa selection rules can eliminate certain dimension-5 operators. In order to be specific we focused on $SU(5)$ models. In particular, we showed that introducing an extra pair of Higgs pentaplets in the standard supersymmetric $SU(5)$, with specific couplings, can eliminate these operators. We also considered the case of the flipped- $SU(5)$ model with extra pentaplets and decuplets and analyzed the conditions for vanishing proton decay through dimension-5 operators. Flipped- $SU(5)$ with extra decuplets was shown to be $D = 5$ operator-free as it happens in the case of the minimal model. However, flipped- $SU(5)$ with extra Higgs pentaplets is not automatically free of dimension-5 operators. We have proposed a solution to this problem which involves a texture of the pentaplet matrix together with certain constraints on the pentaplet couplings to matter.

Acknowledgments

This work is supported by E.U. under the TMR contract "Beyond the Standard Model", ERBFMRX-CT96-0090.

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