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NATURAL TRIPLET-DOUBLET SPLITTING FROM SUPERGRAVITY

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A B S T R A C T

Non-renormalizable terms naturally present in locally supersymmetric GUTs can result in Higgs colour triplets getting large masses, while their weak partners remain light, without fine-tuning of parameters. No $\underline{75}$ representation of $SU(5)$ is needed. This is important since a $\underline{75}$ is disastrous for cosmological scenarios based on local SUSY GUTs.

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The gauge hierarchy problem of grand unified theories - why the Higgs weak doublets are light, while their colour triplet partners are heavy - has inspired a great many attempts to construct models in which this splitting is less mysterious. The introduction of supersymmetry into GUTs¹⁾ has proved to be a giant step forward. The "no renormalization" theorems²⁾ guarantee that a Higgs doublet which is light at the tree level remains light to all orders in perturbation theory^{*)}. The splitting of doublets from triplets then becomes a tree-level problem.

For SUSY GUTs based on $SU(5)$, a solution⁴⁾ to the tree-level splitting problem can be found by introducing chiral superfields transforming as the 50, $\overline{50}$ and 75 representations of $SU(5)$, and including the following terms in the superpotential:

$$W = M_\theta \bar{\theta}\theta + \lambda \bar{\theta} S H + \lambda' \bar{H} S \theta \quad (1)$$

where $\theta = 50$, $\bar{\theta} = \overline{50}$, $H = 5$, $\bar{H} = \overline{5}$ and $S = 75$. The Higgs fields H and $\bar{H}$ couple to quark and lepton fields in the usual way. The 75 is supposed to get a VEV which breaks $SU(5)$ to $SU(3) \times SU(2) \times U(1)$ at a scale M_x . The same VEV will provide a mass term which mixes the colour triplets in H and $\bar{H}$ with those in θ and $\bar{\theta}$. However, there is no weak doublet in the 50, and so the weak doublets in H and $\bar{H}$ remain massless. All components of θ and $\bar{\theta}$ have a bare mass M_θ (which is taken to be of order M_x or larger) and so remain heavy after $SU(5)$ breaks to $SU(3) \times SU(2) \times U(1)$. Since the only modifications of the theory are at the GUT scale M_x , this seems like a harmless and elegant solution.

Unfortunately, it drastically conflicts with cosmological scenarios based on SUSY GUTs. It seems that it is essential to have a potential barrier between the $SU(5)$ symmetric and $SU(3) \times SU(2) \times U(1)$ symmetric phases which is no higher than Λ^4 , where Λ is the confinement scale in the $SU(5)$ phase, typically about 10^9 GeV ⁵⁾. Since a mass term for a symmetry breaking field with vacuum expectation value V contributes a term of order $m^2 V^2$ to the barrier, we must require $m \lesssim \Lambda^2/V$, which is, at most, a few TeV. This means that the 75 must be very light, with a mass much less than M_x or Λ .

*) There are exceptions in both globally and locally supersymmetric theories which include light $SU(3) \times SU(2) \times U(1)$ singlets; see Ref. 3).

But this means that there is no Λ ! A light 75 makes the gauge coupling in the $SU(5)$ phase decrease at lower energies, and so there is no confinement in this phase at all. Furthermore, the presence of these new light particles in the $SU(3) \times SU(2) \times U(1)$ phase changes the renormalization group equations, and prevents perturbative unification.

So we cannot, it seems, have a light 75. In this paper we point out that it is not necessary to have a 75 in models with non-renormalizable couplings in the superpotential. Such couplings are to be expected in supergravity models^{6),7)}, and have already been exploited in cosmological scenarios for locally supersymmetric GUTs⁷⁾⁻¹⁰⁾.

We replace the superpotential of Eq.(1) by

$$W = M_\theta \bar{\theta} \theta + \bar{\theta} H (\lambda_1 M^{-1} \Sigma^2 + \lambda_2 M^{-2} \Sigma^3 + \dots) + \bar{H} \theta (\lambda'_1 M^{-1} \Sigma^2 + \lambda'_2 M^{-2} \Sigma^3 + \dots) \quad (2)$$

where $M = M_p / \sqrt{8\pi} = 2.4 \times 10^{18}$ GeV, and Σ is a light 24 (i.e., its mass is of order M_w). Once Σ acquires a VEV breaking $SU(5)$ to $SU(3) \times SU(2) \times U(1)$, the weak doublets in H and $\bar{H}$ will remain massless, while the colour triplets will have a mass matrix

$$\begin{pmatrix} M_\theta & O(M_x^2/M) \\ O(M_x^2/M) & 0 \end{pmatrix} \quad (3)$$

where M_θ should be of order M_x or larger to avoid having particles from θ and $\bar{\theta}$ influencing the renormalization group equations at scales below M_x . The eigenvalues of this mass matrix are $O(M_\theta)$ and $O(M_x^4/M^2 M_\theta)$. Assuming M_x is between 10^{14} GeV and 10^{18} GeV and M_θ is between M_x and M , this latter eigenvalue is between 10^2 GeV and 10^{17} GeV. The most useful value is about 10^{10} GeV, which occurs, for example, if $M_\theta \approx M$ and $M_x \approx 2 \times 10^{16}$ GeV. In this case the Higgs colour triplets can be used to generate the baryon number of the Universe after the $SU(5)$ to $SU(3) \times SU(2) \times U(1)$ transition, which occurs at a temperature of order Λ^5 . Unlike a light 75, a light 24 does not make the $SU(5)$ gauge coupling decrease at energies below M_x . The previously described cosmological scenarios can proceed without modification.

We have checked to make sure that when Σ gets a VEV in the $SU(3) \times SU(2) \times U(1)$ preserving direction, Eq.(2) does actually induce a mass term for the colour triplets (in principle, it could have vanished). The $\bar{5}_0$ has the following tensor structure:

$$\bar{\theta}_{abcd} = -\bar{\theta}_{bacd} = -\bar{\theta}_{abdc} = \bar{\theta}_{cdab} \quad (4a)$$

$$\bar{\theta}_{abcd} \varepsilon^{abcef} = 0 \quad (4b)$$

The transformation properties of the $\bar{50}$ can be expressed in terms of two 5's, V_a and W_a :

$$\bar{\theta}_{abcd} = (V_a W_b - V_b W_a)(V_c W_d - V_d W_c) \quad (5)$$

The coupling between a 5, $\bar{50}$ and two 24's is given by

$$\bar{\theta}_{abcd} \varepsilon^{abefg} \sum_e^c \sum_f^d H_g \quad (6)$$

The only part of 24×24 which contributes is contained in the 75

$$\begin{aligned} S_{ef}^{cd} = & \sum_e^c \sum_f^d - \sum_e^d \sum_f^c - \frac{1}{12} [\text{Tr}(\Sigma^2)(\delta_e^c \delta_f^d - \delta_e^d \delta_f^c)] \\ & + \frac{1}{3} [(\Sigma^2)_f^d \delta_e^c + (\Sigma^2)_e^c \delta_f^d - (\Sigma^2)_f^c \delta_e^d - (\Sigma^2)_e^d \delta_f^c] \end{aligned} \quad (7)$$

Using Eq.(5) one can easily check that replacing Σ by $\text{diag}(2,2,2,-3,-3)$ results in non-zero mass terms $\bar{\theta}_3 H_3 + \bar{H}_3 \theta_3$ for the colour triplets.

We note that a light 24, in the $SU(3) \times SU(2) \times U(1)$ phase, has light components $(8,1,0) + (1,3,0) + (1,1,0)$; the other components are heavy or absorbed by gauge fields. The light singlet $(1,1,0)$ is potentially dangerous to the gauge hierarchy³⁾. However, in our case there is no tree-level coupling between the two Higgs doublets and the singlet, since there is no coupling like $\bar{H}\Sigma H$ in the superpotential of Eq.(2). Thus, the hierarchy destroying graphs identified in Ref. 3) cannot be drawn; we do not have a light singlet problem.

In conclusion, we have shown how Higgs doublets may be split from Higgs triplets in SUSY GUTs that include non-renormalizable couplings. We do not need to introduce a 75, and so models with acceptable cosmological scenarios can now also enjoy natural doublet-triplet splitting.

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