NATURALLY MASSLESS HIGGS DOUBLETS IN SUPERSYMMETRIC SU(5)

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We construct a supersymmetric SU(5) model characterized by: (a) naturally massless doublet Higgs superfields; (b) the natural appearance of "light" coloured triplet Higgses of mass of the order 10^{10} GeV, and study proton decay as well as the generation of cosmic baryon asymmetry. We find that an appropriate choice of Higgs sector renders dimension-five operators kinematically irrelevant for the stability of the proton. Proton decay proceeds through Higgs boson exchange in terms of dimension-six operators mainly to $\bar{\nu}_\mu K^+$, $\mu^+ K^0$.

It is by now well known that the technical aspect of the hierarchy problem in GUTs, i.e., the stability of scalar masses under radiative corrections [1], is solved by incorporating the concept of global supersymmetry [2]. Nevertheless, a natural explanation for the smallness of M_W is still lacking. In practice one finds that the Glashow–Weinberg–Salam Higgs doublets have to be fine tuned [3] to be essentially massless, while the other members of the Higgs multiplet that carry color must have a mass of at least [4] 10^{10} GeV for fear of too rapid a proton decay. Supersymmetry makes such an arrangement stable to all orders in perturbation theory [5]; however, the masslessness of the Higgs doublets is achieved in a highly unnatural way [3].

Recently, two of us (D.V.N. and K.T.), motivated by the study of the cosmological implications [6] of supersymmetric GUTs, proposed [7] a variety of SU(5) endowed with "light" colour triplets of an intermediate mass in the neighbourhood of 10^{10} GeV. Such a theory leads to [7] $\sin^2\theta_W$ and m_b/m_τ values in agreement with experiment and Higgs boson mediated proton decay through dimension-six operators dominantly to $\bar{\nu}_\mu K^+$, $\nu^+ K^0$ (while dimension-five operators, although present, are irrelevant [8]) as well as a plausible scenario in which monopoles are naturally suppressed and the right amount of matter–antimatter asymmetry is generated [6,9]. In this paper we return to supersymmetric SU(5) to find that the use of the **50** representation leads to naturally massless Higgs doublets as well as Higgs triplets of an intermediate mass (10^{10} GeV). We also carry out an analysis of proton decay in such a model and devise a type of Higgs structure with which dimension-five operators although present are harmless and proton decay proceeds via dimension-six operators mainly to $\bar{\nu}_\mu K^+$, $\mu^+ K^0$. Finally we discuss baryon generation. It should be stressed that apart from setting certain couplings allowed by SU(5) gauge symmetry equal to zero, something made technically possible by the non-renormalization theorem [5] of the superpotential, there is no fine tuning involved in our model. Furthermore, the masslessness of the Higgs doublets is not achieved due to some global symmetry we have imposed, but due to the particular representations we have chosen.

Let us begin by reminding ourselves of the triplet–

doublet problem in SU(5). The relevant terms in the superpotential are [3]

$$W \sim \alpha H_{\bar{5}} \Sigma_{24} H_5 + m H_{\bar{5}} H_5 . \qquad (1)$$

The breaking of SU(5) in the SU(3) × SU(2) × U(1) direction via

$$\alpha \langle \Sigma_{24} \rangle = \tfrac{1}{3} m' \,\mathrm{diag}(2,2,2,-3,-3),$$

leads to

$$W \sim H_{\bar{3}} H_3 (m + \tfrac{2}{3} m') + H_{\bar{2}} H_2 (m - m'). \qquad (2)$$

Choosing $m = m'$ renders the Higgs doublets massless [3]. Nevertheless this extremely accurate adjustment is highly unnatural [3]. If we were to omit the direct mass term, the doublets would obtain superheavy masses from the expectation value of the adjoint Higgs. The strategy we shall use is to introduce representations that contain Higgs triplets but no doublets, so that if we do not put a direct mass term for the 5 and $\bar{5}$ there will be no doublet mass term in the superpotential. A crucial observation is that the **50** representation of SU(5), when decomposed under SU(3) × SU(2) × U(1), contains no SU(3) singlets – SU(2) doublets [1,2]

$$\mathbf{50} = (8,2) + (6,3) + (\bar{6},1) + (3,2) + (\bar{3},1) + (1,1). \qquad (3)$$

No expectation value that would conserve colour and charge is possible for the **50**. Since it is a non-real representation, an anomaly-free supersymmetric SU(5) also requires a $\overline{\mathbf{50}}$. In order to write mixing terms between **5**, $\bar{\mathbf{5}}$ and the $\overline{\mathbf{50}}$, **50** we must use the **75** instead of the **24** representation in order to break SU(5) [‡1].

The list of supermultiplets that define the model is: V_α – gauge vector supermultiplet; Σ(75); θ(50), $\bar{\theta}(\overline{50})$; H(5), $\bar{H}(\bar{5})$ – Higgs supermultiplets; Q^i_{10}, $Q^i_{\bar{5}}$ – matter supermultiplets; the index $i = 1,2,3$ refers to generations.

A superpotential for the model is

$$W = \tfrac{1}{2} M \,\mathrm{tr}(\Sigma^2) + \tfrac{1}{3} a \,\mathrm{tr}(\Sigma^3) + b\theta\Sigma H + c\bar{\theta}\Sigma\bar{H} + \widetilde{M}\bar{\theta}\theta$$
$$+ d Q_{10} Q_{10} H + f Q_{10} Q_{\bar{5}} \bar{H} + h Q_{10} Q_{10} \bar{\theta}. \qquad (4)$$

No term $\bar{H}H$ is present. The coupling h is necessary to avoid any unwanted U(1) global symmetries. A non-zero expectation value for Σ breaks SU(5) *uniquely* to SU(3) × SU(2) × U(1) in contrast with the minimal case in which the 24 leads to degenerate broken vacua [3,11]. The relevant Higgs mass terms would be

$$W \simeq \theta(b\langle\Sigma\rangle H + \bar{\theta}(c\langle\Sigma\rangle)\bar{H} + \widetilde{M}\bar{\theta}\theta + \dots . \qquad (5)$$

The vacuum expectation value of $\langle\Sigma\rangle \sim M/a$ must be of the order of 10^{15}–10^{16} GeV. The resulting SU(3) × SU(2) × U(1) invariant effective superpotential is

$$W \simeq \theta_3 (bM/a) H_3 + \bar{\theta}_3 (cM/a) \bar{H}_3 + \widetilde{M}\bar{\theta}_3\theta_3 + \dots \qquad (6)$$

and does not contain any mass term for the Higgs doublets. The only two scales that are natural in the theory are $M/a \sim 10^{15}$–10^{16} GeV and the Planck mass $\sim 10^{19}$ GeV. We choose $\widetilde{M} \sim M_{\mathrm{Pl}} = 10^{19}$ GeV [‡2]. A reasonable choice for the couplings b, c is $b, c \simeq 10^{-1}$–10^{-2}. Thus, we are led to the following mass matrix for the triplets

$$\mathcal{M} = \begin{pmatrix} 0 & \widetilde{m} \\ \widetilde{m} & \widetilde{M} \end{pmatrix}, \qquad (7)$$

where $\widetilde{m} \sim 10^{14}$–$10^{15}$ GeV and $\widetilde{M} \simeq 10^{19}$ GeV. Diagonalization leads to

$$W \simeq \widetilde{M}\bar{H}_+ H_+ - (\widetilde{m}^2/\widetilde{M})\bar{H}_- H_- , \qquad (8)$$

with

$$H_+ \simeq \bar{\theta}_3 + (\widetilde{m}/\widetilde{M})H_3, \quad H_- \simeq -(\widetilde{m}/\widetilde{M})\bar{\theta}_3 + H_3 .$$

Thus, the triplets H_-, $\bar{H}_-$ obtain a mass roughly of order 10^{10} GeV. It is remarkable that the same Higgs structure that has led us to massless doublets also results in "light" triplets. In such a case, all the "goodies" [7] of a 10^{10} GeV intermediate scale, like $\sin^2\theta_W \simeq 0.22$, $m_b/m_\tau \simeq 2.8$, etc., are automatically reproduced here. Needless to say, this becomes possible only thanks to supersymmetry since radiative corrections will not alter the tree level mass matrix.

Let us next come to the subject of proton decay in our model. Due to the increase of the unification scale in supersymmetric theories, gauge boson mediated proton decay will be suppressed [12]. With Higgs triplets as light as 10^{10} GeV, however, proton decay

‡1 It is interesting to notice that the representations 50 and 75 have been used before, in ordinary GUTs, aiming at a radiatively induced fermion mass spectrum. See ref. [10].

‡2 Setting $\widetilde{M} \simeq 10^{15}$–$10^{16}$ GeV will definitely not undo the natural appearance of massless Higgs doublets, but will certainly evade the appearance of an intermediate mass ($\sim 10^{10}$ GeV) Higgs triplets.

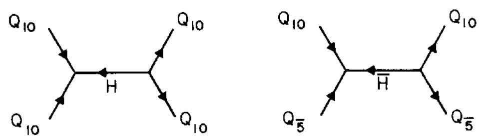

Fig. 1. Diagrams giving rise to dimension six operators.

still occurs at the "usual" rate mediated by coloured Higgs boson exchange [4]. In the case where the breaking of supersymmetry includes a gluino or photino Majorana mass, baryon number violating operators of dimension five also occur [13,14] and with colour triplets of 10^{10} GeV, they lead to too rapid a proton decay. However, as two of us have proposed in a previous paper [8], it is possible to modify the Higgs sector so that dimension-five operators, although present, are not dangerous for the proton for energetical reasons. It is not accidental that the same type of Higgs structure is appropriate for the generation of the baryon asymmetry within our SU(5) model.

The graphs that lead to operators of dimension six are shown in fig. 1. For $m_{\mathrm{H}_3} \simeq 10^{10}$ GeV the rate will be the "usual" $10^{-31}\ (\mathrm{yr})^{-1}$ (roughly) and the decay modes (modulo hadron wavefunction effects) will show the following hierarchical pattern [7]

$$\Gamma(\bar\nu_\mu \mathrm{K}^+;\mu^+\mathrm{K}^0):\Gamma(\bar\nu_\mathrm{e}\mathrm{K}^+;\mathrm{e}^+\mathrm{K}^0;\mu^{+}\text{"}\pi^0\text{"}):\Gamma(\mathrm{e}^+\pi^0;\bar\nu_\mathrm{e}\pi^+)$$
$$\simeq \quad 1 \quad : \quad \sin^2\theta_\mathrm{C} \quad : \quad (\sin^2\theta_\mathrm{C})^2, \tag{9}$$

where $\sin^2\theta_\mathrm{C} \simeq \frac{1}{20}$ is the Cabibbo angle.

On the other hand, dimension-five operators due to the graphs of fig. 2 seem disastrous, giving too high a proton decay rate if $m_{\mathrm{H}_3} \sim 10^{10}$ GeV. It is possible to avoid them by imposing extra symmetries (i.e., an R symmetry [13] or an extra U(1) gauge symmetry [14,15]). If we forbid gaugino Majorana masses, the dangerous graphs vanish. Nevertheless this does not seem the most appealing approach and we shall employ a different strategy [8]. It is known that in order to generate a non-vanishing baryon asymmetry through Higgs triplet decays, we need [8] at least two pairs of Higgs supermultiplets ‡3. At the same time, the fact that the top generation of ordinary fermions has distinctively higher masses than the other two, hints at the existence of Higgs fields that couple exclusively to the top generation. It does not seem unnatural to modify the superspace potential according to

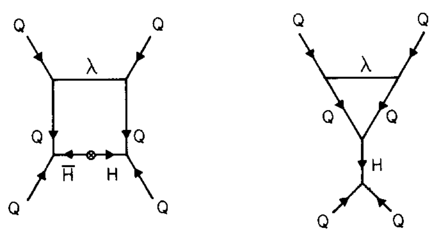

Fig. 2. Diagrams giving rise to dimension five operators.

$$\begin{aligned} W = {} & b\theta^{(1)}\Sigma\mathrm{H}^{(1)} + b'\theta^{(2)}\Sigma\mathrm{H}^{(2)} \\ & + c\bar\theta^{(1)}\Sigma\bar{\mathrm{H}}^{(1)} + c'\bar\theta^{(2)}\Sigma\bar{\mathrm{H}}^{(2)} + \widetilde{M}(\bar\theta^{(1)}\theta^{(1)} + \bar\theta^{(2)}\theta^{(2)}) \\ & + d_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{10}^{(j)}\mathrm{H}^{(1)} + d\mathrm{Q}_{10}^{(3)}\mathrm{Q}_{10}^{(3)}\mathrm{H}^{(2)} \\ & + f_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{\bar5}^{(j)}\bar{\mathrm{H}}^{(2)} + f\mathrm{Q}_{10}^{(3)}\mathrm{Q}_{\bar5}^{(3)}\bar{\mathrm{H}}^{(1)} \\ & + h_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{10}^{(j)}\bar\theta^{(1)} + h'_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{10}^{(j)}\bar\theta^{(2)} + \dots . \end{aligned} \tag{10}$$

We have allowed no $\bar{\mathrm{H}}^{(1)}\mathrm{H}^{(2)}$, $\bar{\mathrm{H}}^{(2)}\mathrm{H}^{(1)}$ as well as $\bar\theta^{(1)}\theta^{(2)}$, $\bar\theta^{(2)}\theta^{(1)}$ terms ‡4. After diagonalization the superspace potential (10) will be

$$\begin{aligned} W \simeq {} & \widetilde{M}(\bar{\mathrm{H}}_+^{(1)}\mathrm{H}_+^{(1)} + \bar{\mathrm{H}}_+^{(2)}\mathrm{H}_+^{(2)}) \\ & - (\widetilde{m}^2/\widetilde{M})(\bar{\mathrm{H}}_-^{(1)}\mathrm{H}_-^{(1)} + \bar{\mathrm{H}}_-^{(2)}\mathrm{H}_-^{(2)}) \\ & + d_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{10}^{(j)}\mathrm{H}^{(1)} + d\mathrm{Q}_{10}^{(3)}\mathrm{Q}_{10}^{(3)}\mathrm{H}^{(2)} \\ & + f_{ij}\mathrm{Q}_{10}^{(i)}\mathrm{Q}_{\bar5}^{(j)}\bar{\mathrm{H}}^{(2)} + f\mathrm{Q}_{10}^{(3)}\mathrm{Q}_{\bar5}^{(3)}\bar{\mathrm{H}}^{(1)} + \dots , \end{aligned} \tag{11}$$

where

$$\mathrm{H}_+^{(1,2)} \equiv \bar\theta_3^{(1,2)} + (\widetilde{m}/\widetilde{M})\mathrm{H}_3^{(1,2)},$$

$$\mathrm{H}_-^{(1,2)} \equiv \mathrm{H}_3^{(1,2)} - (\widetilde{m}/\widetilde{M})\bar\theta_3^{(1,2)}.$$

The only graphs of the type of fig. 2 that we need concern ourselves with are those involving gluino or photino exchange. The SU(2) gauge fermions need not be given a Majorana mass since they will obtain anyway a Dirac mass in combination with Higgs fermions

‡3 One pair of 50 and $\overline{50}$ will not do for reasons we shall explain later.

‡4 Such terms, together with all possible mixings, will appear when supersymmetry is broken; however, they will be of order (m_{SUSY}).

during the SU(2) superHiggs mechanism. The only gauge fermions that might remain massless if the supersymmetry breaking does not contain a Majorana mass for them are the gluino and the photino. Inspecting fig. 2, we observe that the photino or the gluino exchange in the upper part of the box diagram does not mix the generations, which ensures [16] the absence of flavour changing neutral currents. Choosing the down–left vertex of the box diagram to correspond to the $d_{ij} Q_{10}^{(i)} Q_{10}^{(j)} H^{(1)}$ quark coupling that involves all generations, we observe that the down–right vertex will necessary involve only the third generation. The most general type of mixing in SU(5), on the other hand, when all masses are generated by **5**'s and **5̄**'s is

$$Q_{\bar{5}} = \begin{bmatrix} \nu^{(i)} & \\ & d^{c(i)} \\ e^{-(i)} & \end{bmatrix}, \quad Q_{10} = \begin{bmatrix} & (Uu)^{(i)} & \\ e^{+(i)} & & (u^c U^+)^i \\ & d^{(i)} & \end{bmatrix}, \tag{12}$$

where U is the standard mixing matrix.

It is clear then that the down–right vertex in the box diagram of fig. 2, which involves only the third generation if it corresponds to **5̄** and **10** will necessarily mix a ν_τ with b or τ with u, c, t. In both cases for energetic reasons such a diagram would be irrelevant for proton decay. Similarly, if the right–down vertex corresponds to a **10**, **10** coupling it will necessarily mix t with d, s b, which would make proton decay energetically impossible as well. Thus, with the above-chosen Higgs structure, dimension-five operators violating baryon number, although present, are energetically irrelevant for the decay of ordinary nucleons. It should be stressed, however, that alternative ways could be explored in order to tame dimension-five operators. First, by imposing R symmetries [13] or an extra U(1) gauge symmetry [14,15], an alternative that might have an aesthetic appeal to it, or second, by a moderate increase in the supersymmetry breaking scale (~10 TeV) as we have pointed out elsewhere [8].

Let us move next to the generation of the baryon asymmetry in our SU(5) model through the decays of colour triplet Higgses into quarks and squarks [‡5]. In order to obtain a non-vanishing ΔB, the imaginary part of graphs like the one shown in fig. 3 must be

[‡5] Of course, this is only one of several possible mechanisms which will be analyzed in detail elsewhere [17].

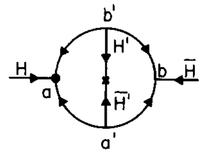

Fig. 3. Two-loop cut graph contributing to the baryon asymmetry.

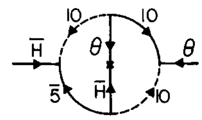

Fig. 4. Two-loop cut graph contributing to ΔB in our model.

non-zero. This requires at least two different pairs of Higgses since

$$\Delta B \propto \mathrm{Im\,tr}\,(aa'bb'). \tag{13}$$

Cut graphs of the type shown in fig. 4, with the superpotential (4), are proportional to $\mathrm{Im\,tr}\,(fhh^*f^*) = 0$ and thus irrelevant. Nevertheless, using the superpotential (10), the same type of graphs as in fig. 4 certainly leads to a non-vanishing

$$\Delta B \propto \mathrm{Im\,tr}\,(f_{33} h^* h' f^*), \tag{14}$$

since the different pairs of θ's and H's couple to quarks with different couplings.

In conclusion, we would like to summarize the main points of the model:

(a) We have obtained massless SU(2) Higgs doublets naturally.

(b) An intermediate scale of order (10^{10} GeV) has naturally arisen, leading to $\sin^2\theta_W \simeq 0.22$ and $(m_b/m_\tau) \simeq 2.8$ in excellent agreement with experiment; colour triplet Higgses of this mass mediate proton decay mainly to $\bar{\nu}_\mu K^+$, $\mu^+ K^0$.

(c) Dimension-five operators can be avoided in proton decay by choosing the appropriate Higgs structure.

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