BARYON ASYMMETRY AND NUCLEON DECAY IN SUPERSYMMETRIC GUTS

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In a class of supersymmetric GUTs with a coloured Higgs sector of an intermediate mass, we study nucleon decay and the generation of baryon asymmetry. We find that: (a) a non-vanishing baryon asymmetry can be generated by the decay of coloured Higgs bosons and Higgs fermions into quarks and squarks; (b) nucleons decay at a rate 10^{-31} yr^{-1} preferably to μ^+K^0, $\bar{\nu}_\mu K^+$ while decay involving dimension-five operators is kinematically excluded.

Recently we proposed [1,2] a variety of supersymmetric GUTs [3] endowed with "light" coloured triplet Higgses of mass of the order of 10^{10} GeV. Such an intermediate scale leads to $\sin^2\theta_W$ and m_b/m_τ values in accordance with experiment [2] as well as to a cosmological scenario [1] in which monopoles are naturally suppressed and the right magnitude of baryon asymmetry is generated. In addition, our scheme predicts a proton lifetime of 10^{31} yr with the characteristic hierarchy of decay modes [2]

$$\Gamma(\bar{\nu}_\mu K^+, \mu^+K^0):\Gamma(\mu^+\text{``}\pi^0\text{''}, \bar{\nu}_e K^+, e^+K^0):\Gamma(e^+\pi^0, \bar{\nu}_e\pi^+)$$

$$\simeq 1 : \sin^2\theta_c : \sin^4\theta_c$$

(modulo hadron wave function effects), which would be a clear sign of the existence of "light" Higgses and at the same time of supersymmetry. In this note we come back to investigate in some detail the question of baryon asymmetry and nucleon decay. As we shall show, these questions are interrelated since the appropriate Higgs structure for the creation of a non-vanishing baryon asymmetry can lead to the suppression of nucleon decay involving dimension-five operators [4].

Let us first review the situation in ordinary GUTs. It is known that [5,6] in the minimal SU(5) model with one Higgs pentaplet no baryon asymmetry can be generated. Gauge bosons are unimportant and Higgs bosons can contribute only through the imaginary part of graphs like those of fig. 1. In the minimal case $a = a'$ and $b = b'$ leading to $\Delta B = 0$. Thus it is

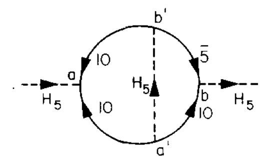

Fig. 1. Diagram contributing to the baryon asymmetry in ordinary SU(5).

clear that at least two colour triplets are needed with different couplings to fermions. Then, a non-vanishing ΔB could arise

$$\Delta B \propto \mathrm{Im}\,\mathrm{tr}\,(ab'b^*a^{*\prime}).$$

It should also be remembered that the masses of the two Higgs bosons should be different, but not too different otherwise the generated baryon number would be suppressed proportionally to their mass ratio squared [6]. Proton decay in ordinary GUTs is dominated by gauge boson exchange. Higgs bosons exchange is suppressed due to the smallness of Yukawa couplings unless the colour triplet bosons are much lighter than 10^{14} GeV. However, if we were to set a Higgs boson mass to be as light as 10^{10} GeV at the tree level, higher-order corrections would tend to renormalize it towards M_X. This is in sharp contrast to the supersymmetric case where non-renormalization theorems [7] would protect it. In addition to that, since in ordinary GUTs baryon production usually occurs around 10^{14} GeV, such "light" Higgses would be irrelevant to the generation of any baryon asymmetry;

on the contrary they may erase any previously produced baryon asymmetry.

The minimal softly broken supersymmetric GUT SU(5) contains two Higgs supermultiplets [3] – a 5 and a $\bar{5}$. Nevertheless no baryon asymmetry can be generated since the imaginary part of the supergraphs analogous to fig. 1 vanishes. Thus, at least two pairs of Higgs supermultiplets with different couplings to quarks are needed. It should be noted, however, that four light SU(2) doublets lead to an unacceptably large value for $\sin^2\theta_W$ in this model. This problem can be avoided [8] by arranging that one pair of doublets obtains a superheavy mass and does not contribute to $\sin^2\theta_W$. Proton decay through gauge bosons is suppressed in this model due to the large value of M_X. The dominant contribution comes from dimension-five operators that can arise from diagrams such as the ones shown in fig. 2. The upper horizontal line corresponds to the exchange of an SU(3) × SU(2) × U(1) gauge fermion. If the soft breaking of supersymmetry includes a Majorana mass term for the gauge fermions, then these graphs are nonzero and dominate proton decay. The dominant decay mode is [9] $p \to \bar{\nu}_\tau K^+$, a signal probably difficult to identify.

Having discussed the main features of GUTs and standard [3] SUSY GUTs as far as proton decay and baryon asymmetry is concerned, we can now proceed to analyze these questions in a supersymmetric GUT with a "light" coloured Higgs sector [1,2]. As we explained, at least four Higgs supermultiplets are needed with different couplings to the quark–lepton supermultiplets. We begin by coupling one pair of Higgses to all generations and one pair only to the top generation. An SU(5) invariant superpotential can be readily written down

$$\begin{aligned}\mathcal{W} = {}& a_{ij}(Q_{10})_i(Q_{\bar{5}})_j H_{\bar{5}}^{(1)} + b_{ij}(Q_{10})_i(Q_{10})_j H_5^{(2)} \\ &+ a_3(Q_{10})_3(Q_{\bar{5}})_3 H_{\bar{5}}^{(2)} + b_3(Q_{10})_3(Q_{10})_3 H_5^{(1)} \\ &+ c\phi H_5^{(1)} H_{\bar{5}}^{(1)} + d\chi H_5^{(2)} H_{\bar{5}}^{(2)} + \tfrac{1}{2} m \operatorname{tr}(\Sigma^2) \\ &+ (e/3!)\operatorname{tr}(\Sigma^3) + f H_5^{(1)} \Sigma H_{\bar{5}}^{(1)} + h H_5^{(2)} \Sigma H_{\bar{5}}^{(2)}, \qquad (1)\end{aligned}$$

where ϕ, χ are SU(5) singlet superfields and Σ is a Higgs supermultiplet in the adjoint representation. Minimization leads to an SU(3) × SU(2) × U(1) invariant effective superpotential

$$\begin{aligned}\mathcal{W} = {}& a_{ij}(Q_{10})_i(Q_{\bar{5}})_j H_{\bar{5}}^{(1)} + b_{ij}(Q_{10})_i(Q_{10})_j H_5^{(2)} \\ &+ a_3(Q_{10})_3(Q_{\bar{5}})_3 H_{\bar{5}}^{(2)} + b_3(Q_{10})_3(Q_{10})_3 H_5^{(1)} \\ &+ m_1 H_3^{(1)} H_{\bar{3}}^{(1)} + m_2 H_3^{(2)} H_{\bar{3}}^{(2)} + \dots . \qquad (2)\end{aligned}$$

Setting $f, h \sim 10^{-6}$ leads to $m_1, m_2 \sim O(10^{10})$ GeV.

We feel justified in coupling a Higgs field exclusively to the third generation since its members are characterized by distinctly higher masses than the members of the other two generations. Notice that the coupling $H_{\bar{3}}^{(1)} H_{\bar{3}}^{(2)}$ is missing from (2). The non-renormalization theorem of the superpotential assures us that (2) will remain unchanged down to energies of order m_W where we expect supersymmetry to be broken. Then one should expect all possible mixing terms between the Higgses to be generated. Thus, if a mixing $H_3^{(2)} H_{\bar{3}}^{(1)}$, $H_{\bar{3}}^{(1)} H_{\bar{3}}^{(2)}$ appears, it will be order m_W. The Cabibbo mixing of quarks is undertaken by the Higgs doublets. Finally, the effective superpotential for the quark couplings to the Higgs triplets will have the form (2) with the quarks replaced by Cabibbo mixed ones. The additional mixings between Higgs triplets will be of order m_W.

Let us now concentrate on the possible sources of a baryon asymmetry in our model. The potentially useful diagrams to lowest order are shown in fig. 3. Thanks to the different couplings of the two pairs of Higgses to quarks and leptons, they indeed have a non-vanishing imaginary part. For example, the Higgs cut diagram 3f will be proportional to

$$\operatorname{Im} \operatorname{tr}(b_3 b_{3i}^* a_{13} a_3^*).$$

In order to finally obtain a non-vanishing baryon asymmetry the masses of the two pairs of Higgses should not be too different, otherwise the rate would be sup-

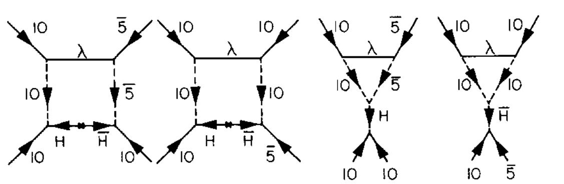

Fig. 2. Baryon-number violating diagrams corresponding to dimension-five operators.

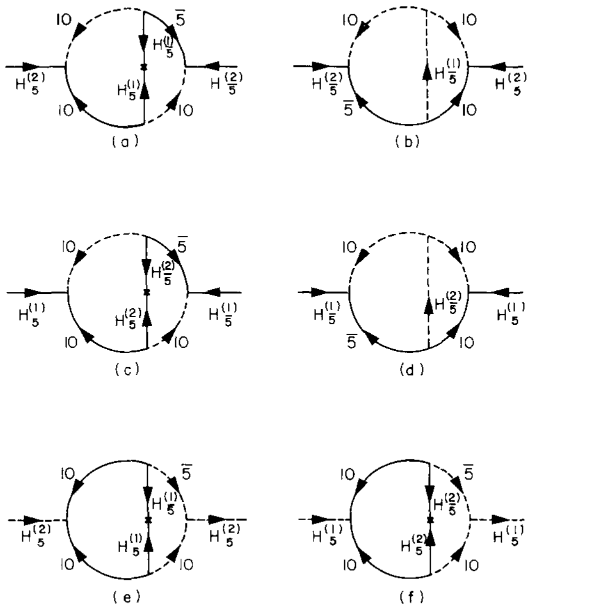

Fig. 3. Diagrams giving rise to baryon asymmetry in supersymmetric SU(5).

pressed proportionally to their ratio squared [6]. Obviously it would be unnatural if this were not the case. Their lifetimes are also automatically different since their couplings to quarks and leptons are different.

Nucleon decay in our model can, in principle, take place via dimension-five and dimension-six operators. Dimension six operators come mainly from Higgs exchange since gauge boson exchange is suppressed due to the large value of the unification mass M_X. As we showed elsewhere in some detail [2], they lead to a characteristic decay mode hierarchy

$$\Gamma(\mu^+K^0, \bar\nu_\mu K^+) : \Gamma(\mu^+\text{“}\pi^0\text{”}, \bar\nu_e K^+, e^+K^0) : \Gamma(e^+\pi^0, \bar\nu_e\pi^+)$$
$$\simeq \quad 1 \quad : \quad \sin^2\theta_c \quad : \quad (\sin^2\theta_c)^2$$

at the “usual” rate 10^{-31} yr^{-1}. Dimension-five operators come from diagrams of the type shown in fig. 4. Graphs of the type shown in fig. 5 are suppressed by a factor m_W/m_{H_3} and thus are irrelevant. If one imposed a symmetry that forbids a Majorana mass for the SU(3) × SU(2) × U(1) gauge fermions then these graphs would be zero. Nevertheless we want to leave open the possibility that a Majorana mass may be present, either as a soft breaking or non-perturbatively,

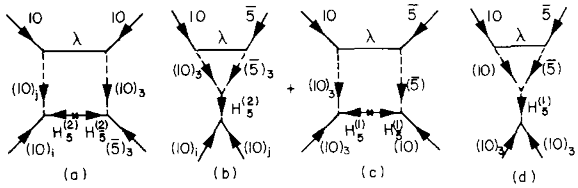

Fig. 4. Diagrams corresponding to dimension-five operators in our model.

and explore the consequences. Since the natural thing to assume is that supersymmetry survives down to the scale of the electroweak breaking, we need not worry about those diagrams that involve W and Z gauge fermion exchange. These fermions will participate in the super Higgs mechanism of the SU(2) × U(1) breaking and obtain a Dirac mass in combination with Higgs fermions instead of a Majorana mass. Then we only need worry about gluino and photino exchange. Concentrating on the graph 4a and starting from the vertex that involves the third generation, we observe that the most general mixing procedure would necessarily lead to $\mu\tau$ or ν_τb. The gluino (or photino) vertex on the other hand does not mix the generations. Therefore nucleon decay through these diagrams would be energetically impossible. The same is true for the triangle graphs 4b. Similarly graphs of the type 4c, d will necessarily involve d or s with t and will be energetically impossible as well. It is amusing to note, however, that even if our Higgs sector allowed for a mixing $H^{(2)}\bar H^{(1)}$ of order 10^{10} GeV we would not necessarily be led to an unacceptable proton decay rate. This goes as follows. The limits obtained by ENR [9] for the Higgs mass m_H are

$$m_{\tilde W}\, m_{H_3} \geqslant (0.4\text{–}4) \times 10^{18}\ \text{GeV}^2,$$

$$m_{sq}^2 m_{H_3}/m_{\tilde g} \geqslant (4\text{–}40) \times 10^{18}\ \text{GeV}^2,$$

where m_{sq} is the squark mass and $m_{\tilde W}$, $m_{\tilde g}$ are the wino and gluino Majorana masses. In the case where

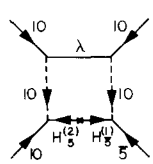

Fig. 5 Suppressed $(m_W/m_{H_3})^2$ baryon-number violating graph.

$m_{\tilde{W}} \ll m_{sq}$ the first inequality should be replaced by

$$m_{sq}^2 m_{H_3}/m_{\tilde{W}} \geqslant (0.4\text{–}4) \times 10^{18}\ \mathrm{GeV}^2$$

(the Dirac mass of the W fermion could be higher than m_{sq}) Then, for $m_{H_3} \sim (10^{10}\text{–}10^{11})$ GeV,

$$m_{sq}^2/m_{\tilde{W}} \geqslant (0.4\text{–}4) \times (10^7\text{–}10^8)\ \mathrm{GeV}$$

$$\simeq 4 \times (10^6\text{–}10^8)\ \mathrm{GeV}.$$

For $m_{\tilde{W}} \simeq 10$ GeV we obtain

$$m_{sq} \geqslant (6\text{–}60)\ \mathrm{TeV},$$

which is not bad at all. Supersymmetry breaking could be tolerated as high as 100 TeV Similarly, for the gluino case, we obtain that, for $m_{\tilde{g}} \sim 10$ GeV, we must have $m_{sq} \gtrsim (20\text{–}100)$ TeV. We should again stress that the Dirac masses for these particles could be much higher.

Let us next summarize the main points of our analysis. As we have shown elsewhere [2], supersymmetric GUTs with coloured triplet Higgses of mass $\sim O(10^{10}$ GeV) lead to $\sin^2\theta_W$ and m_b/m_τ values in accordance with experiment as well as to a scenario [1] with natural monopole suppression and creation of the universal baryon asymmetry. A non-vanishing baryon asymmetry can be generated with two pairs of Higgs supermultiplets through the two-loop cut super graphs (fig. 3). In contrast with other supersymmetric GUTs with no "light" triplets we can easily live with four light doublets without getting too large a value of $\sin^2\theta_W$. Nucleon decay proceeds mainly through six-dimensional operators due to Higgs exchange while dimension-five operators, although not excluded by any symmetry, are kinematically irrelevant for proton decay. Even in the case where we allow for all possible triplet mixings in the superpotential, a reasonable increase in the supersymmetry breaking scale [$\sim O(10$ TeV)] renders dimension-five operators harmless even with Higgs triplets as light as 10^{10} GeV. In that case the characteristic decay mode [9] of nucleons through dimension-five operators, $\bar{\nu}_\tau K^+$, will coexist with the dominant decay modes due to six dimensional operators ($\bar{\nu}_\mu K^+$, $\mu^+ K^0$); the latter, however, are probably much easier to detect.

In conclusion we would like to restate our results. We find that:

(a) Four Higgs supermultiplets are needed in order to obtain a non-vanishing baryon asymmetry.

(b) Dimension-five operators can be kinematically excluded in nucleon decay.

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