BARYON NUMBER VIOLATION IN FUTURE ACCELERATORS ☆

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Received 28 October 1988

As a demonstration of the possibility to observe baryon number violation in the next generation of accelerators we present a semirealistic GUT in which proton decay is forbidden and the unification scale is at $\sim 10^{3-4}$ TeV, leading therefore to observable baryon number violating processes.

Some time ago 't Hooft observed that in gauge theories the configurations with non-vanishing topological charge lead to the anomalous non-conservation of the fermion quantum numbers [1]. This possibility has been applied in the standard electroweak model [2] and causes baryon and lepton number violating processes. The effect was associated with instantons [3] describing the tunnelling transitions between vacua with different fermion numbers, therefore the corresponding amplitudes are expected to be exponentially small without any practical consequence. However, there still exists a possibility that if it has enough energy, the system can pass over the barrier between vacua with different quantum numbers instead of tunnelling through the barrier [4]. Then the exponential suppression of the anomalous amplitudes would be absent. It is very natural and interesting to ask if this possibility can be realized in high energy collisions. However, there exists no satisfactory answer to this question due to the difficulty of estimating the cross section for the formation of a classical gauge field configuration in high energy collisions [5].

Given the spectacular nature of baryon violating processes, if they exist, in particular after the negative results of the proton decay experiments [6], we examine here if this possibility can be realized within the perturbative framework.

In the GUT's perturbative unification it is known how to make the proton stable, when things become uncomfortable with the (non-)detection of proton decay. Since the limits on the proton lifetime rule out the minimal SU(5) [7], it is meaningful to modify the model in such a way as to make the proton stable. For example the proton is stabilized by requiring the lagrangian to be invariant with respect to a global U(1), associated with a quantum number χ, called "chromality" according to the suggestion of refs. [8,9]. Having ensured the stability of the proton [#1] one can imagine that if the theory exhibits instead of a desert, in the intermediate scales between the electroweak and the unification ones, a jungle [11], then the contribution of the new particles in the β functions could lower considerably the unification point and in principle baryon number violating processes could be predicted to be seen in future accelerators. Here we are going to discuss an SU(5) GUT in which the above suggestion is realized.

The model. Consider first the minimal SU(5) model with a 24-plet of Higgs which breaks $SU(5) \to SU(3) \times SU(2) \times U(1)$ and ordinary fermions in 5_R and 10_L. The proton can be stabilized by replacing the $\bar{u}$ in 10_L by $\bar{U}$, a new heavy antiquark, and requiring that the m_U be sufficiently massive in order that the decay $p \to e^+ \bar{U} u$ is energetically forbidden. Having the same quantum numbers, $\bar{u}$ and $\bar{U}$ will mix in general, and proton decay will appear again

☆ Partially supported by the bilateral agreement between Fed. Rep. Germany and Greece.

#1 Other suggestions on proton stability are made in ref. [10].

through this mixing. At this point we introduce a new symmetry to prevent it. We choose this symmetry to be the discrete Z_3. Of course additional representations should be added in order to accommodate the $\bar{u}_L$ and U_L. An anomaly free set of representations is the following:

$$\psi_R^{(1)a}=\underset{5_R}{\begin{pmatrix} e^+ & \\ & d \\ \bar{\nu} & \end{pmatrix}_R}, \quad \psi_L^{(2)ab}=\underset{10_L}{\begin{pmatrix} & u & \\ e^+ & & \bar{U} \\ & d & \end{pmatrix}_L},$$

$$\psi_R^{(3)abc}=\underset{\overline{10}_R}{\begin{pmatrix} & \bar{D} & \\ u & & E^- \\ & \bar{U} & \end{pmatrix}_R}, \quad \psi_L^{(4)abcd}=\underset{\bar{5}_L}{\begin{pmatrix} & E^0 \\ \bar{D} & \\ & E^- \end{pmatrix}_L},$$

$$\psi_R^{(5)abcde}=\underset{1_R}{(E^0)_R}. \tag{1}$$

In order to give masses to the fermions, following ref. [9], we introduce a 5, H_5 and a 45, H_{45}. Requiring all the fermion multiplets to transform under Z_3 as $\exp(2\pi i/3)$, while requiring the Higgs to be invariant, the model has the following Yukawa terms:

$$L_Y(f_{H_5}\bar{\psi}_R^{(1)}\psi_L^{(2)}+g_{H_5}\bar{\psi}_L^{(2)}\psi_R^{(3)}+h_{H_5}\bar{\psi}_R^{(3)}\psi_L^{(4)}$$
$$+k_{H_5}\bar{\psi}_L^{(4)}\psi_R^{(5)})\,H_5^\dagger+\text{h.c.}+(H_5\to H_{45}). \tag{2}$$

The Higgs fields acquire the following non-zero expectation values:

$$\langle H^a\rangle_0=(u/\sqrt{2})\,\delta^{a5}, \quad \langle H_a^{b5}\rangle=v/\sqrt{24}, \tag{3}$$

while

$$H_a^{bc}=-H_a^{cb}, \quad H_a^{ba}=0,$$
$$\langle H_a^{bc}\rangle=0 \quad (b,c\neq 5). \tag{4}$$

From (2), (3) and (4) we find that the fermions (e, d), (u, U), (D, E^-) and E^0 obtain mass contributions from the VEV of the H_5 and in fact they are related by

$$M_5^e=M_5^d, \quad M_5^u=M_5^U, \quad M_5^D=M_5^{E^-}, \tag{5}$$

while $M_5^{E^0}$ is unrestricted.

On the other hand the VEV of the H_{45} gives mass contributions related by

$$M_{45}^e=-M_{45}^d, \quad M_{45}^u=-M_{45}^U, \quad M_{45}^{E^-}=-3M_{45}^D, \tag{6}$$

while there is no contribution to E^0. Therefore both contributions make all the masses arbitrary. Next we would like to introduce additional fermions f's in the 5_R, 10_L, $\bar{5}_L$ and $\overline{10}_R$ representations and two singlets given by

$$f_R^{(1)a}=\begin{pmatrix} f_{E^+} & \\ & f_D \\ \bar{f}_{E^0} & \end{pmatrix}_R, \quad f_L^{(2)ab}=\begin{pmatrix} & f_U & \\ f_{E^+} & & \bar{f}_{U'} \\ & f_{D'} & \end{pmatrix}_L,$$

$$f_R^{(3)abc}=\begin{pmatrix} & \bar{f}_{D'} & \\ f_{U'} & & f_{E'^-} \\ & \bar{f}_U & \end{pmatrix}_R, \quad f_L^{(4)abcd}=\begin{pmatrix} & f_{E'^0} \\ \bar{f}_D & \\ & f_{E'^-} \end{pmatrix}_L,$$

$$f_R^{(5)abcde}=(f_{E'^0})_R, \quad f_L^{(6)}=(f_{E^0})_L. \tag{7}$$

We expect some of these additional particles to obtain masses of the order of the unification scale. In order to achieve that, we require the various elements of the same representation to transform in a different way under certain discrete symmetries [#2]. This can be done for example by identifying elements of the discrete group with the elements of the hypercharge $U(1)_Y$ in SU(5). Given the existence of the above representations, in (7), terms of the form

$$M(f_R^{(1)a}f^{(4)bcde}\epsilon_{abcde}+f^{(2)ab}f^{(3)cde}\epsilon_{abcde}) \tag{8}$$

are permitted by the SU(5) gauge symmetry. We expect M to be of the order of the unification scale. Now we introduce a discrete symmetry $Z_2\times Z_2'$ with elements $Z_2=(0,\,p)$ and $Z_2'=(0,\,p')$ and we identify them with elements of the $U(1)_Y$ (see table 1) setting $p=c/2$ and $p'=6c$. We make the assumptions

Table 1

U_1	$SU_2\times SU_3$ decomposition	SU_5 reps
$\exp(3ic)$	$(2,1)=A$	5
$\exp(-2ic)$	$(1,3)=B$	
$\exp(6ic)$	$(1,1)=C$	10
$\exp(ic)$	$(2,3)=D$	
$\exp(-4ic)$	$(1,3)=E$	

[#2] Such discrete symmetries appear naturally in four-dimensional theories obtained from dimensional reduction of higher-dimensional theories on non-simply connected manifolds [12]; for a review see ref. [13].

$$\begin{array}{lcc} & Z_2 & Z_2' \\ f^{(3)}, f^{(4)}, f^{(5)} & 1 & 1 \\ f_B^{(1)}, f_{D,E}^{(2)} & -1 & 1 \\ f_A^{(1)}, f_C^{(2)} & 1 & -1 \end{array} \qquad (9)$$

where $1, -1$ refer to the quantum numbers under the discrete groups Z_2 and Z_2' it is easy to check that, under $Z_2 \times Z_2'$, lepton mass terms are non-invariant while quark mass terms are invariant. Therefore the requirement of invariance of the lagrangian under this symmetry renders the f-quarks supermassive while it keeps the leptons massless. A new Higgs 5-plet is introduced in order to give mass to those leptons. This Higgs field is assumed to be invariant under Z_2, while it transforms non-trivially under Z_2'. The Yukawa terms are then

$$L_Y = [f_{\phi_5} \bar{f}_R^{(1)} f_L^{(2)} + g_{\phi_5} \bar{f}_L^{(2)} f_R^{(3)} + h_{\phi_5} \bar{f}_L^{(3)} f_R^{(4)} + k_{\phi_5} \bar{f}_L^{(4)} f_R^{(3)}] \phi_5^\dagger + \text{h.c.} + (\phi_5 \to \phi_{45}) + \bar{f}_L^{(6)} f_R^{(1)} \phi_5^\dagger . \qquad (10)$$

Another set of fermionic multiplets appears to be needed in the model which we call g's. The g fermions are like the f's but they have different transformation properties under the discrete symmetry $Z_2 \times Z_2'$. Specifically we require that $g^{(1)}$, $g^{(3)}$, $g^{(4)}$, $g^{(5)}$ are singlets under $Z_2 \times Z_2'$ while $g_c^{(2)}$ is singlet under Z_2 and transforms non-trivially under Z_2'. In this way the corresponding SU(5) invariant mass terms for g's make everything very massive except the SU(2)-singlet lepton appearing in the 10-plets. This singlet lepton can take mass from a Yukawa term $k g_L^{(2)ab} \times g_R^{(3)cde} \epsilon_{abcde} \phi_0$ requiring the singlet ϕ_0 to transform under the discrete symmetries as the $g_c^{(2)}$. The ϕ_0 acquires a VEV at the same order of magnitude as the H's and ϕ's. In order to avoid uninteresting complications, due to large mixing of new fermions coming from different families, we can demand that each of the new family transforms in a different way under a large discrete symmetry.

Next we make a numerical study of the evolution of the three running coupling constants, looking for solutions in which their values lie within the experimental limits at O(80 GeV), while they meet at an appreciably low energy scale.

We find that with one family having the new structure of eq. (1) and two ordinary ones (μ, τ family), plus fifteen families of the "f"-type, sixteen families of the "g"-type and a threshold of 500 GeV for the f's and g's, we obtain unification of the three coupling constants at 4×10^6 GeV with the unified value of the coupling constant $a_u = 0.054$. The renormalization group equations give at 80 GeV the values

$$a_1 = 0.010, \; a_2 = 0.033, \quad a_3 = 0.114,$$
$$\sin^2\theta_w = 0.232,$$

in agreement with the experimental values

$$a_1 = 0.010, \quad a_2 = 0.033 \pm 0.001, \quad a_3 = 0.12^{+0.01}_{-0.02},$$
$$\sin^2\theta_w = 0.228 \pm 0.005.$$

It is interesting that such an early unification can be achieved even at the cost of a jungle of new particles. Since we have excluded proton decay we can look for baryon number violating processes. These processes are shown in fig. 1.

In fig. 1a we show the processes relevant to pp collisions. In the final state they have a new quark and either a charged lepton or missing energy in the form of ν. Note that there is no *s*-channel contribution since u, d and their antiparticles do not appear in the same representation. In fig. 1b we show the relevant graphs for ep machines. In contrast to the previous processes, the *s*-channel contribution is present and also both particles in the final state could be new fermions. The heavier of the exotic fermions (U, D), (E^0, E^-) decay into their SU(2) partners; however, the lighter cannot decay further. The lighter of those exotic fermions, with masses <80 GeV, have the same SU(3)×SU(2)×U(1) interactions as the usual ones and can be produced at the accelerators in

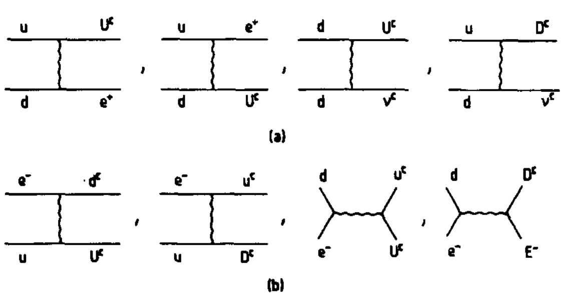

Fig. 1. Diagrams relevant to (a) p($\bar{p}$) collisions and (b) ep collisions.

the same way. Therefore the existence of new heavy stable hadrons and leptons is predicted and could be the signal for the baryon number violating processes.

We find that for the SSC energy and luminosity we are almost at the limit of detecting such processes while for the ep facility planned to be installed in the LEP tunnel things are by two or three orders of magnitude worse.

In conclusion we have presented a unified model based on the gauge group SU(5) in which proton decay is forbidden permitting in this way to add a jungle of new particles in order to lower the unification point. We find that indeed it is possible to lower appreciably the unification point without altering the low energy coupling constants of the standard model. The model predicts baryon number violation to be seen at the next accelerator energies. The obvious cost of this approach is the introduction of a jungle of new heavy particles. Therefore it will be much more interesting to develop a non-perturbative theoretical framework leading to similar results.

We would like to thank P. Langacker and S.D.P. Vlassopulos for helpful discussions, S. Ferrara for reading the manuscript and the Theory Groups of CERN and DESY, where part of this work has been done, for their hospitality.

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