CERN-TH-5415/89

LAPP-TH-252/89

DOES PROTON STABILITY IMPLY THE EXISTENCE OF AN EXTRA Z^0 ?

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Abstract

It is well known that the minimal supersymmetric standard model admits in general Yukawa couplings violating baryon and lepton number. We argue that a generic 4-dimensional $SU(3) \times SU(2) \times U(1)$ string does have in general this type of dangerous couplings. We propose as the most natural solution to the proton stability problem the existence of extra low-energy gauge symmetries ($U(1)$'s) forbidding these terms. We construct in a systematic way the minimal extensions of the supersymmetric standard model in which gauge symmetries forbid all baryon- and/or lepton-number -violating couplings but allow Yukawa couplings for quarks and charged leptons. These models contain an extra $U(1)$ which is not of the E_6 -type.

CERN-TH-5415/89

LAPP-TH-252/89

June 1989

Low-energy supersymmetry (SUSY) was introduced as a cure of the fine-tuning problem associated to Higgs scalars [1]. Although SUSY definitely helps to cope with that problem, it is often not sufficiently remarked that it introduces another, that of proton stability which is absent in the non-supersymmetric standard model. Let us briefly review this problem. The most general superpotential consistent with gauge symmetries and the particle content of the minimal SUSY standard model is given by

$$W = W_1 + W_2 + W_3 \quad (1-a)$$

$$W_1 = h_u Q u_L^c \bar{H} + h_d Q d_L^c H + h_l L E_L^c H \quad (1-b)$$

$$W_2 = h_B u_L^c d_L^c d_L^c + h_L Q d_L^c L + h'_L L L E_L^c \quad (1-c)$$

$$W_3 = \mu H \bar{H} + \mu' L H \quad (1-d)$$

where the standard notation for fields has been used. The coupling constants are tensors in “family space” so that different families are in general mixed. We want the couplings in W_1 to be present so that all fermions get a mass, and also the first term in W_3 , in order to facilitate $SU(2)_L \times U(1)$ symmetry breaking. However, the rest of the couplings violate baryon-number (h_B) or lepton-number (h_L, h'_L, μ') conservation. On the other hand, experimental bounds restrict those couplings to be very small or almost zero. In particular, if both h_B and h_L are of order 1 protons would decay in a few minutes.

In low-energy supersymmetric model building this problem was avoided by demanding conservation of some discrete symmetry which would then imply the vanishing of the unwanted couplings. For instance, one may define a “matter parity” symmetry under which all quarks and leptons get multiplied by (-1) and Higgs fields are inert. The minimal supersymmetric extension of the standard model with this symmetry (or a variation) imposed by hand has been extensively studied in the literature. We investigate in this note the other alternative solution that guarantees proton stability, namely the existence of an extra gauge symmetry beyond the standard model. We present a systematic study for the possible extra Abelian gauge symmetries which are able to forbid fast proton decay and at the same time avoid the neutrino mass problem. Anomaly cancellation strongly restricts the possible $U(1)$ ’s that can be added.

We have been motivated by the consideration of this problem in the context of four-dimensional strings, where we cannot choose at will either the particle content or the symmetries of the low-energy Lagrangian, and therefore there is no a priori reason for a symmetry like matter parity to be present. In fact, in our opinion, there is no really compelling explanation for proton stability in any of the “realistic” models constructed to date. The study of the models considered in this note can then serve as a guide to constrain the phenomenologically interesting string models. We find for instance that they cannot be reproduced from any $(2, 2)$ string vacua since the extra $U(1)$ cannot be embedded in E_6 .

Let us first present some arguments for why in 4-dimensional strings the most natural way to solve the proton stability problem is by means of extra gauge interactions. We will do this by briefly discussing the origin of the different symmetries in string vacua and their possible relevance in explaining proton stability. We will have in mind generic (2,2) and (0,2) compactifications [2,3] obtained through tensoring of $N = 2$ superconformal models (which also include Abelian orbifolds at fixed radii [4]) although we believe that the same arguments apply to other constructions. String compactifications lead to different types of symmetries: *i*) moduli symmetries associated to deformations of the underlying variety (these also include $R \rightarrow 1/R$ duality transformations), *ii*) gauge symmetries and *iii*) discrete symmetries. As remarked in ref. [5] no global continuous symmetries can appear. We want to see if any of these symmetries can be used to forbid fast proton decay. We assume throughout this paper that the standard model gauge group comes entirely from the left-moving world-sheet fermions which give rise to $E_8 \times E_8$ in the heterotic string. If a symmetry is going to forbid fast proton decay, we expect it to be related to flavour symmetries such as B and L conservation and then to act non-trivially on the gauge degrees of freedom. This immediately kills the symmetries of the moduli and any discrete symmetries related only with isometries of the compactified variety or, equivalently, to the internal superconformal field theory ($c = 9$). On the other hand gauge interactions (as well as discrete symmetries coming from their breaking) will generically couple to B and/or L symmetries and can in principle solve the problem. In (2,2) compactifications the gauge group is $E_6 \times E_8$ (an extra factor of rank ≤ 8 is also possible) whereas in (0,2) compactifications, other possibilities exist. Some of the gauge fields originate in the degrees of freedom of the internal $N = 2$ superconformal theory, such is the case of extra $U(1)$'s arising from subtheories in the tensor product. But, as stated above, we assume that they are not related to the standard model group.

Let us briefly describe the origin of discrete symmetries in 4-dimensional strings. For the sake of concreteness, to describe discrete symmetries in 4-d strings we focus on the Z_3 orbifold (or any Z_N orbifold for that matter) [4,6]. Matter fields are divided into untwisted (U) and twisted (T) according to the sector where they appear. Untwisted fields come in three copies. Twisted fields appear in $27 = 3 \times 3 \times 3$ copies associated to the 27 fixed points (3 for each two-dimensional sublattice of the internal $SU(3)^3$ torus). The model has discrete Z_3 symmetries related to “point group” and “space group” invariance. For instance, only couplings $T^{3m}U^n$ are allowed by point group invariance. Space group invariance restricts the possible couplings among twisted fields. For cubic couplings the twisted fields must, in each sublattice, sit all at the same fixed point or all at different fixed points. In general, discrete symmetries and R-symmetries do appear in string models [7-11].

Interestingly enough, discrete symmetries can often be related to broken gauge symmetries. To see this we take again the same Z_3 example. This orbifold can be alternatively constructed as a modding of the model obtained by tensoring nine copies of the level $k = 1$ minimal superconformal theory [12]. The $(k = 1)^9$ model has 8 gauged $U(1)$'s. After modding, two of them are in fact promoted to the full $SU(3)$ group that accompanies $E_6 \times E_8$ in the $(2, 2)$ Z_3 orbifold. The remaining 6 $U(1)$'s are "enhanced" gauge symmetries that from the point of view of the orbifold exist only for specific points in the moduli space of the internal 6-d torus (there are 2 $U(1)$'s for each two-dimensional sublattice). One can check that under these extra $U(1)$'s untwisted fields have integer charges, whereas twisted fields have charges $\pm 1/3$ or $\pm 2/3$ (we can take this as a definition of U and T fields in the $N = 2$ model). Hence, the existence of extra gauged $U(1)$'s implies the vanishing of many couplings [11]. One can also check that the fields (moduli) whose VEV's break the enhanced $U(1)$'s (without breaking the other gauge symmetries nor supersymmetry) are of the untwisted type. From the structure of the couplings allowed by the $U(1)$'s we then see that when they are spontaneously broken (i.e. when we move to less symmetric points in the moduli space of the 6-dimensional torus) discrete Z_3 symmetries survive giving rise to the usual orbifold selection rules mentioned above. This is a realization of the "discrete gauge symmetries" idea recently discussed in ref.[13].

We have then seen that, associated to the internal compactified degrees of freedom, there exist some discrete symmetries that are in fact remnants of broken enhanced gauge symmetries. This is a quite general feature that applies not only to the $(k = 1)^9$ example above but to (at least) all $(2, 2)$ and $(0, 2)$ compactifications obtained from tensoring of $N = 2$ superconformal theories. However, not all discrete symmetries are of this type. A typical example is that of permutations of identical factors in the tensor product. For instance, the $(k = 1)^9$ model is invariant under permutations of the individual factors. This type of symmetries does not always survive in $(0, 2)$ compactifications. For example, adding a Wilson line to one of the three $SU(3)$ tori of the Z_3 orbifold breaks the symmetry under permutations of the three tori. Nevertheless, all these types of discrete symmetries have their origin in the isometries of the internal compactified variety and do not seem to distinguish, e.g., among baryons, leptons and Higgs fields. They have nothing to do with the left-handed gauge world sheet fermions. Contrariwise, these discrete symmetries do distinguish (this is particularly obvious in $(2, 2)$ models) among different generations. Thus, these symmetries are likely to play a rôle in the generation structure and hence in the form of quark and lepton mass matrices but not in proton stability. Of course, they could combine with symmetries originating from the gauge degrees of freedom to generate a symmetry suppressing proton decay. What we mean here is that symmetries originating exclusively from isometries of the

compactifying variety are most likely irrelevant in generating proton stability.

We also know that the couplings in $(1 - c)$ have to vanish essentially for all quark-lepton generations (it is not enough that they vanish for the first generation since Cabibbo mixing will reproduce them through W -exchange). This means that whatever symmetry forbids fast proton decay has to be generation-blind. This further supports the belief that discrete symmetries originating from internal variety isometries are not by themselves relevant for the proton stability problem. We then turn to symmetries originated from free world-sheet fermions or gauge degrees of freedom.

There is another possible source of discrete symmetries that could forbid proton decay. In principle it is possible that once one breaks the large gauge group $(E_6 \times E_8 \times G'$ in $(2, 2)$ compactifications or, e.g., $SO(10) \times G''$ in $(0, 2)$) present in the 4-d string theory, an effective discrete symmetry with the required properties survives. Since the gauge fields usually couple to B and L there is a chance to get a discrete symmetry suppressing proton decay. An example of this possibility, mentioned in ref. [13], is to consider the extra $U(1)$ given by

$$Q_5 = 5(B - L) - 4Y \quad (2)$$

where Q_5 is nothing but the $U(1)$ in $SO(10)$ that commutes with the $SU(5)$ generators. Then, as argued in [13], if some scalars with Q_5 charge ± 4 get a VEV one can easily see that there is a residual unbroken Z_4 symmetry under which all quark and lepton fields (including a right-handed ν_R) transform with a phase $\exp(2i\pi/4)$. This Z_4 symmetry forbids the dangerous couplings in eq. $(1 - c)$. As we will discuss below, a gauge symmetry involving $(B - L)$ is often present in 4-d string models. What is rather unlikely to happen in a string model is to have the required $q_5 = \pm 4$ scalars to do the trick. Notice that if Q_5 is broken by another type of scalars (e.g. fields with the Q_5 -charge of a ν_R) the quark and lepton fields will not transform in the required way and the couplings in W_2 will not be forbidden. Fields with $q_5 = \pm 4$ would have e.g. $L = -4/5$ which, if not impossible, requires very special conditions for a string compactification to do the trick. Furthermore, anomaly-free theories with a gauged $(B - L)$ necessarily include a right-handed neutrino superfield that will have to be relatively heavy in order to understand the smallness of neutrino masses. However, a field with $q_5 = \pm 4$ will never be able to give a mass to a right-handed neutrino that has $q_5 = 5$. A more interesting possibility is to break Q_5 by scalars ϕ with lepton number $L = \pm 2$ so that $q_5 = \pm 10$. In this case these scalars ϕ could give a large mass to right-handed neutrinos through couplings $\phi \nu_L^c \nu_L^c$. It is then easier to consider the generator $(B - L) - 2Y$. Once ϕ gets a VEV, an unbroken Z_2 symmetry remains under which all right-handed fields and Higgses are odd and left-handed fields are even. This forbids all B - and L - violating couplings while allowing standard Yukawa couplings. From the point of view of $SO(10)$ (E_6) unification the ϕ field would be contained in a 126 (351)-dimensional representation, which have

not been found in the massless spectrum in any string vacuum, so that again it is very unlikely for such a mechanism to be available in string models. Hence, we conclude that the existence of residual “discrete gauge symmetries” coming from an underlying gauge symmetry and forbidding fast proton decay is rather unlikely in 4-d strings.

We thus see that obtaining a 4-d string model with proton stability built-in from the beginning is rather difficult. The approach followed in the presently known “realistic” three-generation string models [14-18] generally consists of assuming very specific flat scalar field directions in the process of further gauge symmetry breaking. The idea is to generate an effective “matter parity” or “baryon/lepton” parity forbidding some of the dangerous couplings in W_2 [19]. This parity symmetry is not necessarily a discrete symmetry of the full string model but just an approximate symmetry of the massless sector. However, in order to generate these discrete symmetries one has to assume very special directions for the massless scalar fields. A slight deviation from the chosen field directions again gives rise to fast proton decay.

We would like to illustrate some of the above points with a particular 4-d string, i.e. the three-generation orbifold model of refs. [15,16] (see ref. [10] for a more detailed account). This model is obtained by adding two Wilson lines to one of the $(0, 2)$ versions of the Z_3 orbifold. The resulting gauge group is

$$SU(3) \times SU(2) \times U(1)^8 \times SO(10)' \quad (3)$$

The complete massless spectrum consists of three quark-lepton generations plus a number of extra $SU(3)$ triplets, $SU(2)$ doublets and singlets:

$$\begin{aligned} & 3 [(3, 2) + 2(\bar{3}, 1) + (1, 2) + (1, 1)] + \\ & 3 [4(3, 1) + 4(\bar{3}, 1)] + 3 [12(1, 2) + 56(1, 1)] + 3(16') \end{aligned} \quad (4)$$

One of the $U(1)$ ’s is anomalous and hence a one-loop Fayet-Iliopoulos (FI) term is generated [20]. This FI term triggers further symmetry breaking. The most general flat direction cancelling the FI term leads to an unbroken gauge group

$$SU(3) \times SU(2) \times U(1)_Y \times U(1)_L \times [SO(10)' \times U(1)'] \quad (5)$$

where the gauge group in brackets does not couple to the standard model matter. The gauge group $U(1)_L$ is optional; depending on the flat direction it might or might not be broken. Interestingly enough, most of the exotic particles in eq. (4) get a mass $\sim M_P$ after the symmetry breaking triggered by the FI term takes place. In fact, one is just left with the content of the standard supersymmetric model plus 6 $SU(2)$ doublet pairs and some singlets. If one further chooses a flat direction breaking $U(1)_L$ only, three sets of vector-like heavy leptons survive besides the SUSY standard matter. The Q_L and

u_L^c quarks as well as the $\bar{H}$ Higgs field belong to the untwisted sector whereas the rest of the non-singlet massless fields are contained in the twisted sectors. Thus, one can associate a point group charge P as in table 1. P should be conserved modulo integer. This symmetry implies that only the renormalizable couplings

$$W = h_u Q^i u_L^{cj} \bar{H}^k + h_l L E_L^c H \quad (6)$$

are allowed before the FI term triggers symmetry breaking. The coupling LLE_L^c , which is allowed by P , is forbidden by the $U(1)$ gauge symmetries. In particular, it is forbidden by $U(1)_L$ which couples as lepton number to the standard model fields. An R-symmetry of the model also implies that h_u vanishes unless $i \neq j \neq k$, where these indices label the three generations. Thus, we see that gauge and discrete symmetries forbid most of the couplings in eq. (1). Notice that in any string model no bilinear W_3 superpotential terms exist just on the grounds of scale invariance.

Once symmetry breaking takes place (see ref. [10] for details) the situation changes completely. Many $SU(3) \times SU(2) \times U(1)_Y$ singlet fields (denoted by S_a and Y_i) get VEVs and their non-renormalizable couplings to quarks, leptons and Higgses induce new effective renormalizable Yukawa couplings. Which terms are present can be studied by considering correlation functions of vertex operators

$$\langle V_{-\frac{1}{2}}^F V_{-\frac{1}{2}}^F V_{-1}^B V_0^B \dots V_0^B \rangle \quad (7)$$

where F (B) indicates a fermionic (bosonic) vertex operator. The subindices denote the picture in which the vertex is written [7].

All correlators in eq. (7) consistent with the existing discrete and gauge symmetries are in general non-vanishing. If, in the model we are discussing, one breaks the observable gauge symmetry all the way down to the Standard Model one finds that all the couplings in W_1 and W_2 are generically induced ! (although not for all generations). Hence, the proton is unstable. If, however, one chooses a particular flat direction (scalar singlets $\langle S_4 \rangle = \langle S_7 \rangle = 0$ in the notation of ref. [10]) one gets lepton number conservation ($h_L = h'_L = 0$) by introducing a distinction between the H and L superfields. This is sufficient to guarantee proton stability, although $\Delta B = 2$ processes (e.g. neutron-antineutron oscillations) may occur at rates consistent with experimental bounds. However, proton stability depends on a very specific choice of flat direction. This is a general feature of the “realistic” three-generation models constructed up to now (see e.g. ref. [18]). Thus, for example, in the three-generation Calabi-Yau model of ref. [14] a particular flat direction is chosen (VEVs along $(\lambda_+)_N$ and $(\lambda_-)_{\nu_R}$), in such a way that an effective matter parity is generated. Even if that is the case, extra exotic colour triplets may give rise to fast proton decay unless some dynamical assumptions about exotic masses are made [21].

This dependence of proton stability on a very specific choice of symmetry breaking flat direction is in our opinion a very unattractive feature of the string models built up to now. We have also seen how discrete symmetries present in 4-d strings do not seem to have special relevance for proton stability. Thus, we are led to believe that the most natural solution to the proton stability problem in 4-d strings is the existence of an unbroken gauge symmetry forbidding the dangerous couplings. In fact, this is a way in which proton stability can be guaranteed in the orbifold model described above. If the $U(1)_L$ gauge boson of eq. (5) survives at low energies, it will automatically forbid the lepton number-violating coupling in W_2 and hence the proton will be stable [15]. If, on the other hand, $U(1)_L$ is broken, the dangerous terms will in general be induced by non-renormalizable couplings. One can also explicitly check that no “discrete gauge symmetry” preserving lepton number will be generated either.

Notice that it is very dangerous to talk about naturality in the space of string vacua since any choice of vacuum with a particular gauge group is a sort of fine-tuning, but we are not claiming that string vacua with extra gauge symmetries are going to be preferred once a mechanism for lifting the degeneracy is found. However we all expect that the explanation of proton stability must rely on a deep property of the theory rather than on an adjustment mechanism in the massless sector of the theory. Local symmetries are then in our opinion the most suitable reason for that stability and their effects are expected to survive after supersymmetry is broken. This is in agreement with recent claims [22] about the effects of wormholes at low energies which are supposed to wash out all the symmetries except for the local ones (continuous or discrete). That is, gauge symmetries remain unbroken in the presence of wormhole fluctuations, which is not the case for the discrete symmetries used to stabilize the proton in current 4-dimensional string models. All this points to the preference for extra gauge symmetries surviving at low energies and playing an important role: ensuring proton stability.

Let us then try to answer the following question. What is the minimal extension of the standard model in which baryon and lepton number-violating couplings are forbidden by gauge invariance? The simplest possibility is the existence of an extra gauged $U(1)$, denoted by X , in addition to hypercharge. A strong constraint on X is the cancellation of all gravitational and gauge anomalies. Fulfilment of this constraint depends on the existence of matter beyond the standard content. For instance, if the only matter content were the fields $Q_L, u_L^c, d_L^c, L, E_L^c$, anomaly cancellation (generation by generation) would imply that the only $U(1)$ that can be consistently coupled to them is the standard hypercharge. This fact is very often overlooked in the literature. In fact one can see that cancellation of anomalies (including mixed gravitational anomalies) uniquely fixes the hypercharge assignments of the standard model and hence also charge quantization. Thus one does not need to invoke grand unification nor any

physics beyond the standard model (and Einstein's gravity) to obtain that result. In any event, in this case X would couple like the standard Y and the terms in W_2 would not be forbidden.

As one changes the particle content the possibility of having additional $U(1)$'s different from Y occurs. Adding an $SU(3) \times SU(2)$ singlet N leads to an anomaly-free X that turns out to be a linear combination of Y and $(B - L)$. In particular, we can take $X(Q_L, L) = 0$, $X(u_L^c, N) = 1$ and $X(d_L^c, E_L^c) = -1$. Basically, this is the unique possibility. Thus, interestingly enough, the unique anomaly-free extra $U(1)$ gauge symmetry admitted by the minimal modification (adding a singlet) of the standard model already has the desired properties; the terms in W_2 are forbidden.

We still have to add Weinberg-Salam doublet superfields $H, \bar{H}$ in order to allow for Yukawa couplings giving masses to quarks and leptons. Once this is done, the uniqueness of the extra $U(1)$ is lost. Imposing anomaly freedom leads to the $U(1)$ generators X_1, X_2, X_3 in table 2 (we have allowed for a pair of singlets). To those one has to add the generators obtained by replacing $L \leftrightarrow H$ plus anomaly-free linear combinations. X_1 forbids all the dangerous couplings in W_2 but also the Yukawa couplings in W_1 . On the other hand, the anomaly-free generator

$$T_R = X_1 + X_2 \quad (8)$$

does allow the desired couplings while forbidding B - and L - violating terms. However, the uniqueness is lost, e.g. there are gauged $U(1)$'s that preserve lepton number but not baryon number (X_2 after replacing $H \leftrightarrow L$) and combinations allowing some quark and lepton masses but forbidding others, etc.

T_R in eq. (8) is the only anomaly-free $U(1)$ that forbids B and L violating couplings but allows quark and lepton mass Yukawa couplings. Notice that three new renormalizable couplings are allowed by this gauge symmetry:

$$W_4 = h_\nu L \bar{H} S \quad (9 - a)$$

$$W_5 = h_{S'} H \bar{H} S' \quad (9 - b)$$

$$W_6 = \lambda S'^3 \quad (9 - c)$$

The first would give rise to Dirac neutrino masses once $\bar{H}$ gets a VEV. The second and third may be absent (if S' is absent) and are useful in order to obtain the required pattern of $SU(2) \times U(1)_Y$ symmetry breaking. The term W_4 is necessarily present if one wants to ensure proton stability through a gauged T_R . W_4 could be forbidden by gauging e.g. X_3 , but this is incompatible with a simultaneous gauging of X_1 , as there are $U(1)$ mixed anomalies. Thus, eventually one has to envisage a way in which the right-handed neutrino S gets a large mass so that a "see-saw" mechanism for neutrinos

works. We want to remark that changing the number of doublets or singlets does not change the above results. Finally, the term W_6 also has to be present if one follows the principle of allowing all terms preserving gauge invariance. In fact, if this term were absent a massless Goldstone boson would appear once S' acquires a VEV. This is because a global $U(1)$ symmetry with charges

$$\begin{aligned} Q(d_L^c) = Q(L) = Q(S') &= -1 \\ Q(S) = Q(H) &= +1 \end{aligned} \quad (10)$$

(and vanishing assignments for the rest of the fields) is preserved by the rest of the Yukawa couplings.

The attentive reader has probably realized that the T_R generator in eq. (8) is nothing but the third component of the right-handed weak isospin $SU(2)_R$ present in left-right symmetric models [23]. Of course, it is well known that in those theories $(B-L)$ is gauged. What we wanted to remark with the above discussion is that T_R is not the only possible anomaly-free extra $U(1)$ that can be added to the SUSY standard model and it is not even the only one forbidding fast proton decay (X_1 also does). However, T_R is the only one allowing quark and lepton Yukawa mass couplings. Thus, all this is telling us that one natural way to obtain a stable proton in string models is to start with a model having a left-right symmetric gauge group (like $SU(2)_L \times SU(2)_R \times U(1)$ or $SO(10)$) before further symmetry breaking (e.g. Wilson lines) gives rise to the standard model $\times T_R$.

The advantages of $SO(10)$ Calabi-Yau compactification were remarked in ref. [24] and a symmetry like T_R has been considered in the context of “superstring-inspired” models in ref. [25]. The convenience of a “custodial” unbroken gauge symmetry to suppress proton decay in 4-d string models was discussed in ref. [26]. Notice that a “non-minimal” possibility is to extend the $Y \times T_R$ symmetry to a full $SU(2)_R \times U(1)_{B-L}$ gauge invariance. A 4-d string model with these characteristics was recently constructed [10]. The problem with $SU(2)_R$ models is that the renormalization group prediction for unification scale and $\sin^2 \theta_W$ are rather unrealistic [27].

An obvious possibility that comes to mind is to use the T_3^R right-handed generator that exists in E_6 models since that unification group appears in all $(2, 2)$ compactifications. Things are not so easy, though. Our above statements about the virtues of T_R apply only for the minimal particle content of table 2. E_6 models have extra colour triplets D and $\bar{D}$ with hypercharges $-1/3$ and $1/3$ respectively. Then the new couplings:

$$LQ\bar{D} \ , \ Du_L^c E_L^c \ , \ QQD \ , \ u_L^c d_L^c \bar{D} \ , \ d_L^c DS \quad (11 - a)$$

$$D\bar{D}S' \quad (11 - b)$$

are allowed by the Cartan E_6 generators including T_3^R . The couplings in eq. (11 - a) violate B and/or L and give rise to fast proton decay (if $D, \bar{D}$ are light) through $D, \bar{D}$

exchange. This is a well-known fact in E_6 -based “superstring-inspired” models [28]. Then again one has to rely on the choice of very specific flat directions (see e.g. ref. [21]) in order to suppress the proton decay rate. This is perhaps telling us that starting with an E_6 4-d string model ((2, 2) compactification) is not an advisable way to get a naturally stable proton.

If one adds colour triplets $D, \bar{D}$ to the massless spectrum the number of possible anomaly-free extra $U(1)$ ’s increases. Clearly, two such $U(1)$ ’s are those in the E_6 Cartan subalgebra that have been extensively studied in the literature [28]. However, those $U(1)$ ’s do not forbid the dangerous couplings in eq. (11-a). Let us then extend the massless particle content of table 2 to include also possible colour triplets D and anti-triplets $\bar{D}$ and search for the most general extra anomaly-free $U(1)$ which forbids B and L violation. It is a straightforward exercise to impose all the conditions for anomaly cancellation (including non-Abelian, Abelian and mixed gravitational anomalies). The result of the analysis shows that there are two families of solutions for hypercharge and extra $U(1)$ assignments (see table 3). We have assumed that the extra $U(1)$ allows the Yukawa couplings in eq. (1-b). We will denote by Q_R and Q_A the $U(1)$ generators of the corresponding two families. Let us discuss them in turn.

In the Q_R case, the standard hypercharge and Q_R assignments of D and $\bar{D}$ are arbitrary (but opposite). The Q_R quantum numbers for the rest of the fields are like those of T_R in eq. (8). In order to forbid the couplings in eq. (10-a) one must have

$$m \neq 0 \quad , \quad x \neq -2a \quad (\text{or } y \neq 0) \quad (12)$$

in table 3. Notice that the most general renormalizable superpotential will be of the type

$$W = W_1 + W_4 + W_5 + W_6 + W_7 \quad (13)$$

where

$$W_7 = h_d D \bar{D} S' \quad (14)$$

Thus a Dirac mass for neutrinos will be given by the coupling W_4 . To avoid conflict with experiment, a way has to be found by which the right-handed neutrinos (S fields) acquire a large mass, i.e. $m_S \gtrsim 10^3$ GeV. The simplest way in which that could happen is by introducing a couple of chiral superfields $N, \bar{N}$ with Q_R charges m and $-m$ respectively. Then the following Yukawa couplings will be allowed by gauge invariance:

$$L \bar{H} N + S \bar{N} S' + N \bar{N} S' \quad (15)$$

If the field $\bar{N}$ develops a large VEV ($\gtrsim 10^3$ GeV) and if the singlets S' come in three copies (one per generation), the three right-handed neutrinos S will combine with the

S' fields and will disappear from the low energy spectrum. Notice that in the present model the fields $H, \bar{H}, D, \bar{D}$ and $N, \bar{N}$ may come in just one copy whereas the rest of the spectrum comes in three generations.

For a special choice of the parameters in the Q_R family of generators ($x = -2a, y = m$), Q_R admits an interpretation in terms of an $SO(10)$ generator. In this case one can identify $Q_R = (B - L) - 2Y$. However one must assign $B - L$ charges $+1/3$ and $-1/3$ to the D and $\bar{D}$ fields. Then Q_R may be identified with the third component of the $SU(2)_R$ gauge group present in left-right symmetric models like $SO(10)$ if the $D, \bar{D}$ fields belong to the 16 and $\bar{16}$ representations of $SO(10)$, and not to the 10 , as happens in E_6 -based models. In this case the couplings

$$d_L^c DS' + Q \bar{D} H \quad (16)$$

are also present. Notice that if S' gets a VEV, the fields d_L^c and D combine and become massive. In this case one should identify the standard d, s and b quarks with linear combinations of d_L^c and $\bar{D}$ fields.

Another possibility in the Q_R class of models is the choice $x = -2a$ and $m = 2y$. In this case all B - and L - violating terms vanish except for a coupling ($u_L^c \bar{D} \bar{D}$). This term vanishes unless there is more than one generation of $\bar{D}$ fields since the $SU(3)$ contraction is antisymmetric.

In the Q_A family of solutions, D and $\bar{D}$ have opposite hypercharges but are flipped in the sense that $Y(D) = Y(d_L^c) = -Y(\bar{D})$. This flipping is essential to forbid B - and L - violating processes. The singlets S and S' have opposite hypercharge and Q_A charge so that they are not really required to get anomaly cancellation. All B - and L - violating couplings are forbidden as long as $l \neq 0$. For arbitrary w, z , the $D, \bar{D}$ and $H, \bar{H}$ fields do not couple to the S, S' singlets. The existence of these two couplings is desirable in order for the $D, \bar{D}$ to get eventually a mass and also in order to facilitate the electroweak symmetry breaking. If one wants the terms W_5 and W_7 to be generated, one has to choose $w = 0, z = l$. Then automatically neutrino Yukawas ($L \bar{H} S$) also appear. There are two ways to avoid the neutrino mass problem. First, one can get rid of the S, S' singlets altogether (or else choose $z \neq l$). Then the neutrino Dirac mass is forbidden. In fact Q_A is the unique extra $U(1)$ which simultaneously forbids B - and L - violation as well as Dirac neutrino masses. As we remarked above this possibility has the shortcoming that the couplings $(D \bar{D} S'), (H \bar{H} S')$ are also forbidden. A second alternative is to give large masses to the candidate right-handed neutrinos S, S' . In fact S and S' can combine to get a gauge invariant mass e.g. by coupling to another singlet S'' with zero hypercharge and Q_A and letting S'' acquire a non-vanishing VEV.

Notice that a model with a gauged Q_A symmetry necessarily requires the extra fields $D, \bar{D}, H, \bar{H}$ to come in three copies. Thus it has the attractive property that the

presence of low-energy Higgs fields $H, \bar{H}$ is required to get cancellation of anomalies. This is not the case in models with a gauged Q_R symmetry nor the SUSY standard model in which the presence of Higgs doublets is imposed by hand. Notice also that the Q_A charge can be considered as an anomaly-free gauged extension of the global symmetry of eq. (10). Once Q_A is broken, the would-be axion is swallowed by the corresponding Q_A gauge boson to become a massive new Z^0 .

Let us summarize our results concerning extra $U(1)$ gauged symmetries forbidding fast proton decay. In the absence of extra coloured triplets we have seen that the $U(1)$ forbidding B - and/or L - violation while allowing for the standard Yukawa couplings is essentially unique. It is given by T_R in eq. (8) and table 2 and it may be identified with the diagonal generator of the gauged $SU(2)_R$ symmetry appearing in left-right symmetric models like $SO(10)$. When one includes colour triplets $D, \bar{D}$ in the massless sector, there are two families Q_R and Q_A of extra $U(1)$'s with the required properties (table 3). None of them can be embedded in E_6 with matter in the 27. Let us remark that extra massless colour triplets appear easily in 4-dimensional strings even if they are not of the E_6 type. In fact, the existence of as many $D, \bar{D}$ as $H, \bar{H}$ pairs is welcome from the point of view of the low-energy renormalization group equations. The SUSY standard model with just a pair of Higgs doublets predicts a unification mass $M_{GUT} \simeq 10^{16}$ GeV (adding more doublets decreases this value). Adding a $D, \bar{D}$ pair (with hypercharge $Y = \pm 1/3$) for each $H, \bar{H}$ leads to $M_{GUT} \simeq 10^{18}$ GeV $\simeq M_P$, as it should.

It would be quite interesting to work out in detail the phenomenological consequences of the above models. The most obvious of them is, of course, the existence of a new extra Z' gauge boson. Present neutral current data [29] gives the lower bound $M_{Z'} \gtrsim 300$ GeV for $U(1)$ charges of the T_R and Q_R types discussed in the text. Proton stability puts an upper bound on $M_{Z'}$. Once supersymmetry and the extra $U(1)$ are broken, B and L violating terms will in general be induced by loops, giving rise to couplings of the order

$$h \sim \left(\frac{g}{2\pi} \right)^n (M_{Z'}/M_P) \quad (17)$$

An actual value for the proton decay rate will depend on details of each model, but one does not expect e.g. values $M_{Z'} \gg 10^7$ GeV to be compatible with the observed proton stability.

We conclude by stating the main points of this letter. We have argued that the proton is generically unstable in string models unless some fine-tuning of scalar field VEVs is made. The natural solution to this problem is the existence of ‘‘custodial’’ gauge interactions beyond the standard model forbidding B - and L - violating couplings but allowing for the usual Yukawa couplings. In the standard SUSY model those dangerous terms are forbidden by imposing discrete symmetries (R-parities). We have investi-

gated in this note the alternative approach of forbidding those couplings by means of gauge invariance. In particular we have made a systematic analysis of possible extra $U(1)$ symmetries beyond the standard hypercharge which can ensure proton stability. Cancellation of anomalies strongly restricts the possibilities. We find essentially two families of extra $U(1)$ generators with the required properties. None of them can be embedded into E_6 with matter in the 27. We hope to address further phenomenological consequences of this class of low-energy supersymmetric models in the near future.

ACKNOWLEDGEMENTS. We thank C. Burgess for useful remarks. We are indebted to J. Rostant for a thoroughful reading of the manuscript(s).

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TABLE 1

	Q	u_L^c	d_L^c	L	E_L^c	H	$\bar{H}$
$6Y$	1	-4	2	-3	6	-3	3
L	0	0	0	1	-1	0	0
P	0	0	1/3	1/3	1/3	1/3	0

Table 1: Hypercharge, $U(1)_L$ charge and point group quantum numbers of the standard model fields in the model of refs. [10,15].

TABLE 2

	Q	u_L^c	d_L^c	L	E_L^c	H	$\bar{H}$	S	S'
$6Y$	1	-4	2	-3	6	-3	3	0	0
X_1	0	1	-1	0	-1	0	0	1	0
X_2	0	0	0	0	0	1	-1	0	0
X_3	0	0	0	0	0	0	0	1	-1

Table 2: Anomaly-free $U(1)$'s coupled to the shown matter superfields.

TABLE 3

	Q	u_L^c	d_L^c	L	E_L^c	H	$\bar{H}$	S	S'	D	$\bar{D}$
$6Y$	a	$-4a$	$2a$	$-3a$	$6a$	$-3a$	$3a$	0	0	x	$-x$
Q_R	0	m	$-m$	m	$-m$	m	$-m$	m	0	y	$-y$

(a)

	Q	u_L^c	d_L^c	L	E_L^c	H	$\bar{H}$	S	S'	D	$\bar{D}$
$6Y$	a	$-4a$	$2a$	$-3a$	$6a$	$-3a$	$3a$	w	$-w$	$2a$	$-2a$
Q_A	0	0	$-l$	$-l$	0	l	0	z	$-z$	l	0

(b)

Table 3: Hypercharges and Q_R (Q_A) assignments for the two classes of extra $U(1)$ generators ensuring proton stability.