Exotic Baryon-Number Nonconservation: Another E_6 Superstring Variation

Ernest Ma
Department of Physics, University of California, Riverside, California 92521
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A supersymmetric gauge model based on E_6 particle content which conserves lepton number but not baryon number is derived from the requirement of a single, simple Z_2 discrete symmetry. The proton is stable because no physical final state having zero lepton number is available for its decay. Neutrinos are massless and left-handed as in the standard model or one is massless and left-handed while the other two are massive Dirac particles. Interesting experimental consequences of this model abound. Some are briefly discussed.

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Well-motivated theoretical extensions of the standard model which include more particles and interactions at energies within reach of the next generation of accelerators are clearly not devoid of interest. In the context of superstring theory, a candidate model of this kind[1] is the supersymmetric SU(3)⊗SU(2)⊗U(1)⊗U(1)′ gauge model populated by particles belonging to the **27** representation of E_6. Now it is also generally assumed that those terms in the superpotential which are not allowed by E_6 are absent as well in the low-energy theory. Hence there is an additional global U(1)″ symmetry which serves to differentiate between particles transforming identically under the low-energy gauge group. Note that U(1)″ can be broken by soft terms in the Lagrangean which also break the supersymmetry. In Table I, the various components of the **27** are listed against their SU(3)⊗SU(2)⊗U(1)⊗U(1)′⊗(1)″ contents. The known particles are of course Q, u^c, d^c, L, and e^c, where the superscript c denotes charge conjugation and all states are taken to be left-handed. Without the global U(1)″, d^c, L, and N^c are indistinguishable from h^c, E, and S, respectively. With the global U(1)″, the model is still invariant under the simultaneous exchange of the two sets of fields. However if the low-energy gauge group is not exactly as given, this switch would correspond to different physics.[2]

TABLE I. Transformation properties of the various components of the **27** representation under SU(3)⊗SU(2)⊗U(1)⊗U(1)′⊗U(1)″.

	SU(3)	SU(2)	U(1)	U(1)′	U(1)″
Q	**3**	2	$\frac{1}{6}$	$\frac{1}{3}$	$-\frac{1}{12}$
u^c	**3***	1	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{12}$
d^c	**3***	1	$\frac{1}{3}$	$-\frac{1}{6}$	$\frac{3}{4}$
L	**1**	2	$-\frac{1}{2}$	$-\frac{1}{6}$	$\frac{3}{4}$
e^c	**1**	1	1	$\frac{1}{3}$	$-\frac{1}{12}$
E	**1**	2	$-\frac{1}{2}$	$-\frac{1}{6}$	$-\frac{2}{3}$
$\bar{E}$	**1**	2	$\frac{1}{2}$	$-\frac{2}{3}$	$\frac{1}{6}$
S	**1**	1	0	$\frac{5}{6}$	$\frac{1}{2}$
N^c	**1**	1	0	$\frac{5}{6}$	$-\frac{11}{12}$
h	**3**	1	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{6}$
h^c	**3***	1	$\frac{1}{3}$	$-\frac{1}{6}$	$-\frac{2}{3}$

There are eleven possible terms in the superpotential. Five are necessary for the spontaneous generation of fermion masses, namely $Qu^c\bar{E}$, Qd^cE, Le^cE, $SE\bar{E}$, and Shh^c for m_u, m_d, m_e, m_E, and m_h, respectively. Hence the neutral scalar components of $\bar{E}$, E, and S must pick up vacuum expectation values. Of the remaining six terms, a few must be absent to prevent rapid proton decay. Therefore, some additional effective symmetry at low energies is inevitable for such models. Consider now the simplest possibility, i.e., a single Z_2 discrete symmetry. It has already been shown[3] that Q, u^c, and d^c can be chosen to be even in this case without loss of generality. Consequently, at least eight models can be defined depending on whether (L,e^c), N^c, and (h,h^c) are even or odd, as detailed in Table II. The corresponding allowed and forbidden terms are indicated in Table III. Models 6 and 8 are not realistic because rapid proton decay is unavoidable. Model 7 is fine, but h has very little to do here, and is stable. Models 1 and 2 are natural first choices and have been discussed extensively.[4] The term $LN^c\bar{E}$ generates a nonzero Dirac neutrino mass and must have a very small coupling. Hence it may be desirable to forbid it so that the three known neutrinos either are exactly massless or pick up small masses through radiative

TABLE II. Possible transformation properties of (L,e^c), N^c, and (h,h^c) under Z_2.

Model	L,e^c	N^c	h,h^c	Comment
1	−	−	−	$B=\frac{1}{3}$, $L=1$ for h
2	−	−	+	$B=-\frac{2}{3}$, $L=0$ for h
3	−	+	−	Model B of Ref. 3
4	+	−	−	Model A of Ref. 3
5	−	+	+	To be discussed
6	+	−	+	Rapid proton decay
7	+	+	−	Stable h
8	+	+	+	Rapid proton decay

TABLE III. Allowed (√) and forbidden (−) terms in the various models defined in Table II and in the text.

	1	1′	2	3	4	5	6	7	8
$LN^c\bar{E}$	√	−	√	−	−	−	−	√	√
QLh^c	√	√	−	√	−	−	√	−	√
u^ce^ch	√	−	−	√	−	−	√	−	√
d^cN^ch	√	√	−	−	√	√	−	−	√
QQh	−	−	√	−	−	√	√	−	√
$u^cd^ch^c$	−	−	√	−	−	√	√	−	√

corrections.[5] The latter turns out to be impossible if the discrete symmetry does not distinguish among generations.[6] However, a simple model[7] does exist for three or more generations where a Z_3 discrete symmetry is added to distinguish among generations in the $\bar{E}$, E, and S sectors. This is listed in Table III as model 1′. If $LN^c\bar{E}$ is forbidden only for that $\bar{E}$ which has a nonzero vacuum expectation value, then models 3 and 4 are the same as the ones discussed in Ref. 3. Model 5 is then the only one left to be discussed and it appears at first sight that it will also cause rapid proton decay as models 6 and 8 do, and must be discarded. But that would be too hasty a decision. After all, N^c is not a known particle. If it is indeed the right-handed mass partner of the neutrino, then certainly $p \to \pi^+ N^c$ is possible and model 5 is ruled out. However, if N^c has a mass greater than the proton, then the model may still be in the running. In what follows it will be shown that this is indeed a realistic model and some of its rather unusual consequences will be discussed.

Let the superpotential of model 5 be given by

$$W=\lambda_1 Qu^c\bar{E}+\lambda_2 Qd^cE+\lambda_3 Le^cE+\lambda_4 SE\bar{E}+\lambda_5 Shh^c +\lambda_6 QQh+\lambda_7 u^cd^ch^c+\lambda_8 d^cN^ch. \quad (1)$$

Then h, h^c, and N^c must all have lepton number $L=0$ and baryon number $B=-\frac{2}{3}$, $\frac{2}{3}$, and 1, respectively. Contrast this with the conventional assignment of $L=-1$ and $B=0$ for N^c in models 1 and 2 as required by the $LN^c\bar{E}$ term. Here this term is absent, and there is no actual connection between ν and N^c. Each is a separate massless particle and can take on unrelated quantum numbers. As it is, the model conserves both B and L, with $p \to \pi^+ N^c$ almost immediately. This is of course unacceptable. However, if the scalar component of N^c acquires a nonzero vacuum expectation value, then N^c will become massive through mixing with a gauge fermion or with other neutral $L=0$ fermions, as will be shown in detail later, and the above decay can be forbidden. Furthermore, even though baryon number is no longer conserved, lepton number still is. Therefore, the proton is stable because no physical $L=0$ final state is available for its decay. Massless neutrinos are now only three in number for three generations as in the standard model, instead of six as in models 1 and 2. The astrophysical upper limit[8] is of course only four, and so models 1 and 2 may be in trouble already unless the mass scale for U(1)′ breaking is much higher than for SU(2)⊗U(1).

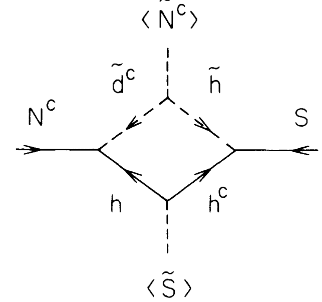

FIG. 1. One-loop contribution to the N^cS mass in the presence of the soft supersymmetry-breaking $\tilde{d}^c\tilde{h}\tilde{N}^c$ term.

The term d^cN^ch in Eq. (1) actually has 27 possible couplings for three generations. These can be divided into three sets of nine according to which N^c is involved. Call them $\lambda_8^{(i)}$, $i=1,2,3$. Let N_1^c be the fermion whose scalar partner has a nonzero vacuum expectation value y; then its coupling to the gauge fermion corresponding to U(1)′ will allow it to pick up a mass. The mass matrix spanning the two states is of the form

$$m=\begin{pmatrix} 0 & g_1'y \\ g_1'y & \mu \end{pmatrix}, \quad (2)$$

where g_1' is the U(1)′ gauge coupling, and μ is an allowed Majorana mass term which breaks the supersymmetry but not the gauge symmetry. In models 1 and 2, this mechanism can be applied[9] in a 3×3 mass matrix including also one particular neutrino ν to obtain a small Majorana mass for ν, conserving B but not L in the process. Here, since N^c starts out with $L=0$ and $B=1$ instead of $L=-1$ and $B=0$, it is L and not B which is now conserved. Consequently, N^c can mix with other $L=0$ fermions but not with ν $(L=1)$. All three known neutrinos remain massless in this model. Note that of the five neutral fermions in each generation, only ν has $L=1$ while all others have $L=0$. This means that N^c can pick up a mass by pairing up with S, for example. A typical diagram is depicted in Fig. 1. An order-of-magnitude estimate for such a mass is a few gigaelectronvolts if all unknown masses are a few hundred gigaelectronvolts and all unknown couplings are not suppressed relative to the gauge couplings. Therefore, N_2^c and N_3^c are expected to have masses in this range because $\lambda_8^{(2)}$ and $\lambda_8^{(3)}$ are not phenomenologically restricted to be small. On the other hand, $\lambda_8^{(1)}$ is proportional to the amount of d-h mixing, so that it has to be very small.[10] Fortunately, N_1^c acquires its mass through Eq. (2) independent of $\lambda_8^{(1)}$. A rough estimate of its magnitude is $g_1'y$, which is a few hundred gigaelectronvolts.

Note that d-h mixing is consistent with lepton-number conservation as long as $m_\nu=0$, a condition which has already been pointed out.[11]

Another consequence of $y \neq 0$ is the possible existence of a pseudo-Goldstone boson.[10] This comes about because the global symmetry $B-L$ is spontaneously broken. However, $B-L=2(Y_L+Y_R)$ is part of E_6, where Y_L and Y_R refer to the weak hypercharges in the decomposition $E_6 \supset SU(3)_C \otimes SU(3)_L \otimes SU(3)_R$, so that if $U(1)''$ is local instead of global, there would not be a Goldstone boson. On the other hand, local $U(1)''$ is broken at a high mass scale, and so the would-be Goldstone boson here will pick up a very small mass from effective nonrenormalizable interactions which break $B-L$ symmetry. Experimentally, the nonobservation of $K \to \pi +$ nothing means again a very small $\lambda_8^{(1)}$. A technical difficulty here exists[10] because a small $\lambda_8^{(1)}$ may be incompatible with a large y if the spontaneous symmetry breaking is driven by the evolution of parameters from the Planck scale down to a few hundred gigaelectronvolts. Alternatively, if B symmetry is allowed to be broken by soft terms which also break the supersymmetry but not the gauge symmetry, such as $\tilde{d}^c \tilde{h} \tilde{S}$, then the would-be Goldstone boson will be able to pick up a large mass and a large y will also be possible. However, the mechanism for soft supersymmetry breaking in such models is not well understood and it is not clear how L is to be conserved in this sector while B is not. Of course, if the model is regarded merely as an extension of the standard model without worrying about its possible superstring antecedent, then there are no technical problems. In fact, with these soft terms, except for the problem of n-$\bar{n}$ oscillation to be discussed later, there is no need for $y \neq 0$. Hence d-h mixing can be avoided and $\lambda_8^{(1)}$ is not necessarily small, while N_i^c $(i=1,2,3)$ will still be able to pick up masses of a few gigaelectronvolts as shown in Fig. 1 with $\langle \tilde{N}^c \rangle$ replaced by $\langle \tilde{S} \rangle$.

Proton stability.—Although baryon-number conservation is violated in this model, the proton is stable because lepton number is still conserved. Systems of two or more particles with total angular momentum $\frac{1}{2}$ and $L=0$ such as $\pi^+ N^c$ and $\pi^+ e^+ \tilde{e}$ are all heavier than the proton.

Properties of N^c.—Since the direct interaction of N^c always involves heavy particles such as h or the $U(1)'$ gauge boson, it is not easily produced. A possible scenario is for the strongly interacting h or $\tilde{h}$ to be produced in a hadron collider, for example, and then N^c to be found in the decays $h \to \tilde{d} N^c$ or $\tilde{h} \to d N^c$. The decay of N^c itself is into udd $(u^c d^c d^c)$ consisting of channels such as $\pi^- p$ $(\pi^+ \bar{p})$ or $\pi^0 n$ $(\pi^0 \bar{n})$ with an amplitude proportional to $\lambda_6 \lambda_8 / m_{\tilde{h}}^2$, which is certainly not greater than G_F. Hence the width of N^c is at most of the order $G_F^2 m_{N^c}^5$ which is about 0.4 keV for $m_{N^c}=5$ GeV. Consequently, it is hopeless to see N^c as a resonance in low-energy $\pi^- p$ scattering, for example.

Absence of a stable supersymmetric particle.—Since

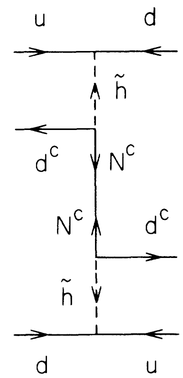

FIG. 2. Effective six-quark interaction for n-$\bar{n}$ oscillation.

B invariance is broken, $R \equiv (-1)^{2j+3B+L}$ is also not conserved, and so the lightest supersymmetric particle in this model is not stable. For example, the photino $\tilde{\gamma}$ can mix with N^c through a diagram analogous to that shown in Fig. 1, and decay into $\pi^- p$ $(\pi^+ \bar{p})$ and $\pi^0 n$ $(\pi^0 \bar{n})$ as well. Of course, it must be assumed that $m_{\tilde{\gamma}} > m_p - m_\pi$ or else $p \to \pi^+ \tilde{\gamma}$ would be possible. This opens up an intriguing possibility, namely that supersymmetric particles may have already been produced at present accelerators, but the photino may not carry away missing momentum, unless it lives long enough to be stable within the detector. In conventional models where R invariance is broken because L invariance is broken, the photino can still be tracked by its decay $\tilde{\gamma} \to \gamma \nu$, but here the decay products are pions and nucleons which disappear easily into the background.

Neutrinos.—There are three massless left-handed neutrinos as in the standard model. All other neutral fermions, twelve Higgs and three gauge, have $L=0$ and mix with one another. A variation of the model allows for one massless left-handed neutrino and two massive Dirac neutrinos, as will be discussed.

Neutron-antineutron oscillation.—One effective interaction which changes a neutron into its antiparticle through gluino exchange has already been discussed in the literature.[12] Another is depicted here in Fig. 2, which actually is forbidden if N^c has only a Dirac mass. This would be the case if each N^c pairs up with a separate two-component spinor exclusively to form a four-component spinor. However, because there is, in general, mixing among all fifteen $L=0$ neutral two-component spinors in this model, each N^c is a linear combination of fifteen Majorana spinors and they can enter with different signs. The sum of all three contributions to the n-$\bar{n}$ transition amplitude is then restricted by the experimental limit[13] of about 3 years on the oscillation lifetime. However, barring accidental cancellations, the effective Majorana masses for N_2^c and N_3^c are probably not much less than a few gigaelectronvolts which would then induce an n-$\bar{n}$ transition several orders of magnitude greater than is allowed. There are two ways to escape the above conclusion. The first is to postulate that N_2^c and N_3^c do not couple to the d quark but only to the s and b quarks. This is possible but not very satisfactory because there is no symmetry which can maintain such a separation; hence fine tuning of parameters is needed. The second is to postulate that N_2^c and N_3^c do not couple to quarks at all. This can be achieved by making N_2^c and N_3^c odd under Z_2; hence the model becomes a hybrid of models 2 and 5. From Table III, it can be seen that N_2^c and N_3^c will now pair up with two of the three left-handed neutrinos to form massive Dirac particles. Since N_2^c and N_3^c can now be assigned $L=-1$, and L is still exactly conserved, they do not contribute at all to Fig. 2. A bonus of this solution is that it allows for neutrino oscillations and thus offers a natural explanation of the solar-neutrino puzzle in terms of the Mikheyev-Smirnov-Wolfenstein effect.[14]

With the assumption now that only N_1^c contributes to Fig. 2, the n-$\bar{n}$ mass difference is then estimated to be

$$\Delta m \sim (\lambda_6 \lambda_8^{(1)} / m_{\tilde{h}}^2)^2 \mu (g_1' y)^{-2} |\psi(0)|^4,$$

where $|\psi(0)|^2$ is the probability density of finding two quarks at the same point in the neutron and is usually assumed to be given by[15] $|\psi(0)|^2 \simeq (\pi R^3)^{-1}$, where R is the neutron radius of the order 1 fm. The quantities μ and $g_1' y$ are those of Eq. (2), and $g_1' y$ is probably a few hundred gigaelectronvolts, but the value of μ is unknown and is assumed to be much smaller than $g_1' y$ for convenience. Let $m_{\tilde{h}} = 1$ TeV, $g_1' y = 500$ GeV; then $[\lambda_6 \lambda_8^{(1)}]^2 \mu < 3 \times 10^{-10}$ GeV, which is not unexpected because $\lambda_8^{(1)}$ has to be very small to avoid any appreciable d-h mixing in the first place. For example, if $\lambda_6 = 2 \times 10^{-2}$, $\lambda_8^{(1)} = 10^{-4}$, then $\mu < 75$ GeV. Note that these numbers also correspond to a lower limit of about 10^{33} years on the deuteron lifetime. If y/m_h turns out to be much greater than $m_{\tilde{d}}^2 / m_{\tilde{h}}^2$, the previously mentioned contribution to Δm from gluino exchange[12] is then likely to be the more dominant.

In conclusion, a supersymmetric gauge model in which baryon number is assigned also to a neutral color-singlet fermion N^c and its invariance is then spontaneously and softly broken at a few hundred gigaelectronvolts is shown to be consistent with all present data and leads to new and interesting physics yet to be explored experimentally.

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