Particle dichotomy and left-right decomposition of E_6 superstring models

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In supersymmetric E_6 gauge models based on superstring theory, an exactly conserved multiplicative quantum number can be defined to separate all particles into two groups. This dichotomy is especially important if left-right symmetry is realized at low energies. It makes possible a truly massless Dirac neutrino whose right-handed component is effectively inert and a second W boson with a mass perhaps as low as 300 GeV in a model with unconventional particle assignments.

The low-energy particle content of superstring theory[1-3] may well consist of a few supermultiplets in the **27** representation of E_6 and gauge bosons and fermions corresponding to a subgroup G of E_6. The most popular version of G is $SU(3)\times SU(2)\times U(1)\times U(1)$ and many studies have been made[4-7] in its name. Another possibility for G is $SU(3)\times SU(2)\times SU(2)\times U(1)$ which results in an extended version of left-right-symmetric models. Although details of the symmetry-breaking mechanism which interpolates between the physics at the Planck scale and that of the electroweak scale are yet to be understood, many general features of the low-energy theory are of clear phenomenological interest. In this paper, it is shown that after the spontaneous symmetry breaking of G as well as the breaking of supersymmetry, an exactly conserved multiplicative quantum number can emerge which separates all particles in such models into two groups. For the known particles and their supersymmetric partners, this quantum number coincides exactly with the well-known R parity in most models of supersymmetry which makes the lightest supersymmetric particle, usually the photino, stable. Here, it may also be used to make the neutrino exactly massless. Furthermore, it can be applied to a model with unconventional left-right particle assignments so that there can be a second W boson with a mass perhaps as low as 300 GeV without running into conflict with low-energy experimental constraints or the astrophysical limit on the number of neutrinos.

Consider the [SO(10),SU(5)] decomposition of a single **27** of E_6:

$$\mathbf{27}=(16,\bar{5})+(16,10)+(16,1)+(10,\bar{5})+(10,5)+(1,1)\ . \tag{1}$$

The known quarks and leptons of one generation are conventionally assumed to be contained in the $(16,\bar{5})$ and (16,10). Take the first generation as an example; then, in the notation of Ref. 4,

$$(16,\bar{5})=d^c(\bar{3},1,\tfrac{1}{3},-\tfrac{1}{6})+\begin{bmatrix}\nu_e\\ e\end{bmatrix}(1,2,-\tfrac{1}{2},-\tfrac{1}{6})\ , \tag{2}$$

$$(16,10)=u^c(\bar{3},1,-\tfrac{2}{3},\tfrac{1}{3})+\begin{bmatrix}u\\ d\end{bmatrix}(3,2,\tfrac{1}{6},\tfrac{1}{3})+e^c(1,1,1,\tfrac{1}{3})\ , \tag{3}$$

$$(16,1)=N^c(1,1,0,\tfrac{5}{6})\ , \tag{4}$$

$$(10,\bar{5})=h^c(\bar{3},1,\tfrac{1}{3},-\tfrac{1}{6})+\begin{bmatrix}\nu_E\\ E\end{bmatrix}(1,2,-\tfrac{1}{2},-\tfrac{1}{6})\ , \tag{5}$$

$$(10,5)=h(3,1,-\tfrac{1}{3},-\tfrac{2}{3})+\begin{bmatrix}E^c\\ N_E^c\end{bmatrix}(1,2,\tfrac{1}{2},-\tfrac{2}{3})\ , \tag{6}$$

$$(1,1)=n(1,1,0,\tfrac{5}{6})\ , \tag{7}$$

where each particle's $SU(3)\times SU(2)\times U(1)\times U(1)$ content is also displayed. The last U(1) leads to an extra neutral gauge boson beyond the standard model. The superscript c denotes the charge-conjugate state; hence, ψ_L^c can be interpreted as ψ_R. Note that $(16,\bar{5})$ and $(10,\bar{5})$, as well as (16,1) and (1,1), are equivalent representations under $SU(3)\times SU(2)\times U(1)\times U(1)$.

There are 5 neutral-scalar fields in each **27** representation which may acquire nonzero vacuum expectation values: namely, $\tilde{\nu}_e$, $\tilde{N}^c$, $\tilde{\nu}_E$, $\tilde{N}_E^c$, and $\tilde{n}$. Specifically, m_u comes from $\langle\tilde{N}_E^c\rangle$, m_d and m_e come from $\langle\tilde{\nu}_E\rangle$, m_h and m_E come from $\langle\tilde{n}\rangle$, while $\langle\tilde{\nu}_e\rangle$ and $\langle\tilde{N}^c\rangle$ cause d to mix with h and e to mix with E, and the 5×5 neutral-lepton mass matrix receives contributions from all 5. Clearly, the vacuum expectation values $\langle\tilde{N}_E^c\rangle$, $\langle\tilde{\nu}_E\rangle$, and $\langle\tilde{n}\rangle$ must all be nonzero, but $\langle\tilde{\nu}_e\rangle$ and $\langle\tilde{N}^c\rangle$ need not be. In the following, it will be assumed that in fact $\langle\tilde{\nu}_e\rangle$ and $\langle\tilde{N}^c\rangle$ are zero. Consider now the following assignment of R parity. All gauge bosons are even; all gauge fermions are odd. The known quarks and leptons are even; their supersymmetric scalar partners are odd. The new quark h and the new leptons E, ν_E, N_E^c, and n are *odd*; their supersymmetric scalar partners are *even*. The neutral lepton N^c may be either even or odd; its supersymmetric scalar partner $\tilde{N}^c$ is then odd or even. Since only $\langle\tilde{\nu}_E\rangle$, $\langle\tilde{N}_E^c\rangle$, and $\langle\tilde{n}\rangle$ are nonzero, the spontaneous breaking of the gauge symmetry does not violate the conservation of this extended version of R parity.

Phenomenologically, the existence of the above-mentioned multiplicative quantum number has several important consequences. In the neutral-lepton sector, ν_e pairs off with N^c to form a Dirac neutrino and decouples from ν_E, N_E^c, and n. If N^c has even (odd) R parity, the mass term $\nu_e N^c\langle\tilde{N}_E^c\rangle$ is allowed (forbidden), hence, the possibility of an exactly massless ν_e. In any case, since N^c (as well as ν_e) transforms nontrivially under the extra

U(1) in G, the astrophysical limit[8] on the number of neutrinos, i.e., 4, may force[9] the extra neutral gauge boson to be many times heavier than the standard W and Z. In the quark sector, since d and h have opposite R parity, there is no $Zh\bar{d}$ coupling, etc., and many of the conjectured scenarios[4–7] for experimental discovery at future high-energy accelerators are now not applicable. On the other hand, the unitarity of the 3×3 Kobayashi-Maskawa matrix is now assured, because there is no mixing between the known quarks and the new ones. The hadronic production of h is just like that of any other heavy quark, but its decay must now be into supersymmetric scalar partners of the usual quarks and leptons via Yukawa couplings. Some possible decay modes are $d\tilde{\nu}_e$, $u\tilde{e}$, $\nu_e\tilde{d}$, and $e\tilde{u}$. The scalar quarks and leptons will then decay into the corresponding quarks and leptons together with gluinos and photinos as in any other model of supersymmetry. Similarly, some of the decay modes of E are $\tilde{u}\bar{d}$, $\bar{\nu}_e\tilde{e}$, etc. As for ν_E, N_E^c, and n, their mass matrix is of the form

$$M=\begin{bmatrix}0 & A & B\\ A & 0 & C\\ B & C & 0\end{bmatrix}, \tag{8}$$

where A, B, and C come from $\langle\tilde{n}\rangle$, $\langle\tilde{N}_E^c\rangle$, and $\langle\tilde{\nu}_E\rangle$, respectively. Hence all three neutral leptons mix in general and their decay will be into $\bar{u}\tilde{u}$, $\bar{d}\tilde{d}$, $\bar{e}\tilde{e}$, $\bar{\nu}_e\tilde{\nu}_e$, etc.

Suppose now that $G=SU(3)\times SU(2)\times SU(2)\times U(1)$, then the particle assignments of Eqs. (2)–(7) become

$$(u,d)_L:(3,2,1,\tfrac{1}{6}), \tag{9}$$

$$(d^c,u^c)_L:(\bar{3},1,2,-\tfrac{1}{6}), \tag{10}$$

$$(\nu_e,e)_L:(1,2,1,-\tfrac{1}{2}), \tag{11}$$

$$(e^c,N^c)_L:(1,1,2,\tfrac{1}{2}), \tag{12}$$

$$h_L:(3,1,1,-\tfrac{1}{3}), \tag{13}$$

$$h_L^c:(\bar{3},1,1,\tfrac{1}{3}), \tag{14}$$

$$\begin{bmatrix}\nu_E & E^c\\ E & N_E^c\end{bmatrix}_L:(1,2,2,0), \tag{15}$$

$$n_L:(1,1,1,0). \tag{16}$$

Again, R parity can be defined as before, except now N^c can only be even (and $\tilde{N}^c$ odd), because N^c goes together with e^c. Hence R parity cannot be used to keep ν_e and N^c massless in this case. The appearance of a second SU(2) means that right-handed charged currents must be considered in all weak decays. Since ν_e combines with N^c to form a Dirac neutrino, polarized μ^+ decay[10] constrains the mass of a second W boson to be greater than about 400 GeV. On top of that, there is a new 3×3 charged-current mixing matrix for the known quarks in the right-handed sector and if it is similar to the Kobayashi-Maskawa matrix, the K_L-K_S mass difference requires[11] m_{W_2} to be greater than about 1.6 TeV. The astrophysical limit on the number of neutrinos is also relevant because N^c transforms nontrivially under G. Therefore, it is quite likely that the physics associated with the second SU(2) in this model will not show up directly below a TeV or so.

Consider next the following model. Switch the assignments of the supermultiplets $(16,\bar{5})$ and $(10,\bar{5})$, as well as $(16,1)$ and $(1,1)$. As noted before, this makes no difference in the $SU(3)\times SU(2)\times U(1)\times U(1)$ realization, but if the effective low-energy G is really $SU(3)\times SU(2)\times SU(2)\times U(1)$, a remarkably interesting model is revealed. Specifically, the particle assignments are

$$(u,d)_L:(3,2,1,\tfrac{1}{6}), \tag{17}$$

$$d_L^c:(\bar{3},1,1,\tfrac{1}{3}), \tag{18}$$

$$(h^c,u^c)_L:(\bar{3},1,2,-\tfrac{1}{6}), \tag{19}$$

$$h_L:(3,1,1,-\tfrac{1}{3}), \tag{20}$$

$$\begin{bmatrix}\nu_e & E^c\\ e & N_E^c\end{bmatrix}_L:(1,2,2,0), \tag{21}$$

$$(e^c,n)_L:(1,1,2,\tfrac{1}{2}), \tag{22}$$

$$(\nu_E,E)_L:(1,2,1,-\tfrac{1}{2}), \tag{23}$$

$$N_L^c:(1,1,1,0). \tag{24}$$

Again, let it be assumed that only $\tilde{\nu}_E$, $\tilde{N}_E^c$, and $\tilde{n}$ have nonzero vacuum expectation values; then R parity can be defined as before. The only difference is that W_2 must now be *odd,* and its supersymmetric fermion partner even. All other gauge bosons (fermions) remain even (odd), all known quarks and leptons remain even and their supersymmetric scalar partners odd, while h, E, ν_E, N_E^c, and n are odd and their supersymmetric scalar partners even as before. Again, N^c may be either even or odd, and $\tilde{N}^c$ odd or even, corresponding to whether the mass term $\nu_e N^c\langle\tilde{N}_E^c\rangle$ is allowed or not. Hence an exactly massless ν_e is again possible. In the 5×5 mass matrix for the neutral leptons, ν_e again pairs off with N^c to form a Dirac neutrino, but now N^c transforms trivially under G, so it is effectively inert and there is no problem with the astrophysical limit on the number of neutrinos. The right-handed charged current links e with n, but n is presumably heavy, so there is no constraint on m_{W_2} from polarized μ^+ decay. Similarly, since W_2 does not couple to d and s quarks, m_{W_2} is not constrained by the K_L-K_S mass difference either. In fact, since the R parity of W_2 is odd, it can only be produced in pairs or in association with another particle of odd R parity. Consequently, no firm experimental lower limit on m_{W_2} is known. However, there is a limit[12] of about 350 GeV on the second Z boson in such models, and since the main breaking of $SU(2)_2$ is achieved via $\tilde{n}$ which is part of an $SU(2)_2$ doublet, m_{W_2} cannot be much smaller, and a lower limit of 300 GeV would not be an unreasonable estimate. Clearly, this model allows a much lighter W_2 than the conventional left-right model.

Remarkably, the quark structure of this model is identical to that of a model proposed many years ago.[13] As in that model, W_1 cannot mix with W_2, and that paves the way for the possibility of a massless neutrino. Recall that in the conventional left-right model, a diagram connecting W_1 and W_2 via a fermion loop is infinite, implying the need for a counterterm. Hence W_1 and W_2 must mix in the conventional model, and a two-loop diagram connecting ν_e and N^c to e through W_1-W_2 mixing is also infinite,[14] so ν_e cannot be massless unless W_1 is somehow forbidden to mix with W_2. Here, all such would-be infinite contributions are zero by virtue of R parity.

In this model, in addition to the decay modes into scalar quarks and leptons mentioned previously, h can also decay into uW_2 if kinematically allowed. The decay of W_2 itself is likely to be into en, because n is probably the lightest of all the new particles with odd R parity. This can be seen from the structure of Eq. (8). In the context of the unconventional left-right assignments of Eqs. (17)–(24), C breaks $SU(2)_1$, A breaks $SU(2)_2$, and B breaks both. Hence A should be greater than B or C. Now m_h and m_E come from A, and the 3×3 mass matrix of Eq. (8) tends to pair off ν_E with N_E^c giving them a Dirac mass equal to A, so n should be the lightest. Of course, n is not a mass eigenstate, but it only mixes a little with ν_E and N_E^c if B/A and C/A are small. If the conventional left-right assignments of Eqs. (9)–(16) are used, then A breaks neither $SU(2)_1$ nor $SU(2)_2$, while B and C break both. This pattern of symmetry breaking is known to be inconsistent with what is experimentally observed. Although such a situation can be remedied by postulating additional supermultiplets beyond those needed for three generations, it really cannot compare with the unconventional left-right model, where all would-be problems are solved naturally with such ease. The decay of n will be into $\gamma\tilde{\gamma}$ through one-loop diagrams involving $E\tilde{E}$, etc.

Some more remarks are in order concerning this model. The new lepton E can have decay modes like any other heavy lepton, i.e., $E\to(\nu_E,N_E)W_1\to(\nu_E,N_E)e\bar{\nu}_e$, etc., but since ν_E and N_E are essentially the left-handed and right-handed components of the same Dirac particle, the coupling of E to W_1 is vectorial. The new particle h has been called a quark because it is a triplet under color SU(3), and E a lepton because it is a singlet. However, if the usual definitions of baryon number B and lepton number L for the known quarks and leptons are to be maintained, the following quantum numbers should be assigned in this model: h has $B=\frac{1}{3}$ and $L=1$; E, ν_E, N_E^c, and n all have $B=L=0$; N^c has $B=0$ and $L=-1$; W_2^- has $B=0$ and $L=1$; all other gauge bosons have $B=0$ and $L=0$; and each particle's supersymmetric partner has the same B and L assignments as the particle. In the conventional left-right model, flavor-changing neutral currents are unavoidable because two or more scalar vacuum expectation values are needed for each quark mass to make up realistic mass matrices. Specifically, the problem has to do with the fact that $\tilde{\nu}_E$ and $\tilde{N}_E^c$ both belong in the scalar multiplet (1,2,2,0). In this model, $\tilde{\nu}_E$ is in $(1,2,1,-\frac{1}{2})$ instead, and that allows realistic mass matrices to be constructed with only one $\langle\tilde{\nu}_E\rangle$ for m_d and m_e, one $\langle\tilde{N}_E^c\rangle$ for m_u, and one $\langle\tilde{n}\rangle$ for m_h and m_E, etc. Therefore, the unconventional assignments of Eqs. (17)–(24) not only give the correct pattern of left-right-symmetry breaking, they also render possible the natural suppression of flavor-changing neutral currents.

In conclusion, a model based on $SU(3)\times SU(2)\times SU(2)\times U(1)$ as the effective low-energy gauge group of particle interactions has been proposed. Supermultiplets in the **27** representation of E_6 as inspired by superstring theory are considered, with specific assignments as given by Eqs. (17)–(24). The definition of R parity used in most models of supersymmetry is extended to include new particles and a second W boson. The resulting model allows an exactly massless neutrino whose right-handed component is effectively inert so that the astrophysical limit on the number of neutrinos can coexist with a relatively low mass for W_2. Other experimental and phenomenological constraints on m_{W_2} are also not applicable. In the context of this model, prospects of many new physics discoveries exist in forthcoming and proposed high-energy accelerators.

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