Prominent Decay Modes of a Leptophobic Z' [1]

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Abstract

An anomaly-free U(1) charge Q' has recently been identified within the group E_6 for which the familiar leptons (the left- and right-handed electron and the left-handed neutrino) have $Q' = 0$. It is pointed out that the Q' charges of several *exotic* leptons within E_6 matter multiplets are quite large, leading to the prediction that half of the decays of the so-called "leptophobic" Z' bosons coupling to Q' are to these exotic leptons. Other large Q' charges include those of standard up-type quarks and exotic down-type quarks. Substantial forward-backward asymmetries are expected in $u\bar{u} \to Z' \to f\bar{f}$ channels when f is a standard up-type quark, an exotic down-type quark, or an exotic lepton.

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It has recently been proposed [1, 2, 3] that searches for new neutral gauge bosons Z', traditionally pursued at the highest energies using the reaction $\bar{p}p \to Z' + \ldots \to (e^+e^- + \ldots$ or $\mu^+\mu^- + \ldots)$ [4], may have overlooked such bosons if they are *leptophobic*, i.e., if their couplings to the standard leptons are suppressed. The interest in such Z' states extends beyond the specific motivations of Refs. [1] and [2], which sought to explain an excess branching ratio $B(Z \to b\bar{b})$ [5] and an excess of jets produced at high transverse momenta in $\bar{p}p$ collisions [6] with respect to standard-model predictions.

Although a leptophobic Z' might appear somewhat artificial from the standpoint of unified theories of the electroweak and strong interactions, such a state has recently been constructed using the U(1) charges available within the group E_6 [7]. In this note we wish to point out that this Z', although its couplings shun the traditional leptons, decays half the time to *exotic* leptons which are contained within the matter multiplets of E_6. Such leptons are part of the complement of fermions which are required in order that the U(1) be anomaly-free. We shall also note that the couplings of this state favor up-type quarks over down-type quarks, in contrast to those of the standard Z.

Candidates for groups unifying color SU(3) with electroweak SU(2) $\times$ U(1) include SU(5), SO(10), and E_6. The SU(5) group [8] is the smallest with which this unification can be achieved; the familiar left-handed fermions belong to a $\mathbf{5}^*+\mathbf{10}$-dimensional reducible representation. With the addition of a right-handed neutrino, these two representations may be combined in a single $\mathbf{16}$-dimensional spinor of SO(10) [9]. This, in turn, is contained in a $\mathbf{27}$-dimensional representation of E_6, which is a group often encountered in superstring theories [10] but whose possibilities for strong-electroweak unification were explored before the superstring era [11]. In addition to the SO(10) $\mathbf{16}$-plet, the $\mathbf{27}$ of E_6 contains representations of (SO(10), SU(5)) with dimensions ($\mathbf{10}$, $\mathbf{5}^*+\mathbf{5}$) and ($\mathbf{1}$, $\mathbf{1}$).

Extra-U(1) factors can be identified in various ways. A maximal subgroup of SO(10) containing SU(5) includes an additional U(1) which is conventionally labelled U(1)$_\chi$, while a maximal subgroup of E_6 containing SO(10) includes an additional U(1) called U(1)$_\psi$ [12, 13, 14]. One particular combination of these two U(1)'s is frequently discussed in the context of superstring theories [10] and is called U(1)$_\eta$. (More details on searches for extra Z's, including Z_η, may be found in Refs. [15].) The leptophobic Z' constructed in Ref. [7] couples to a linear combination of U(1)$_\eta$ and the weak hypercharge belonging to the U(1) of the standard electroweak theory.

For our purposes it is more convenient to label the U(1) factors within E_6 by means of the isospins and weak hypercharges in the decomposition $E_6 \to$SU(3)$_C\times$ SU(3)$_L\times$ SU(3)$_R \to$SU(3)$_C\times$SU(2)$_L\times$U(1)$_L\times$SU(2)$_R\times$U(1)$_R$ [10]. The $\mathbf{27}$-plet of E_6 consists of $(\mathbf{3},\mathbf{3},1) + (\mathbf{3}^*,\mathbf{3}^*,1) + (1,\mathbf{3},\mathbf{3}^*)$ of SU(3)$_C\times$ SU(3)$_L\times$ SU(3)$_R$, i.e., a color triplet of quarks, a color antitriplet of antiquarks, and a nonet of color-singlet leptons. The electromagnetic charge Q is then given by

$$Q = I_{3L} + \frac{Y_W}{2} \equiv I_{3L} + I_{3R} + \frac{Y_L + Y_R}{2} \quad . \tag{1}$$

Unnormalized charges corresponding to $U(1)_\chi$ and $U(1)_\psi$ may be expressed [10] as

$$Q_\chi = 4I_{3R} - 3(Y_L + Y_R) \quad , \quad Q_\psi = 3(Y_R - Y_L) \quad , \tag{2}$$

while a charge corresponding to $U(1)_\eta$ is a linear combination of these [10]:

$$Q_\eta = 3I_{3R} - 6Y_L + (3/2)Y_R \quad . \tag{3}$$

The authors of Ref. [7] note that it is possible to include in the Lagrangian a term mixing the field strength $B_{\mu\nu}$ of weak hypercharge $U(1)_{Y_W}$ with the field strength $X_{\mu\nu}$ of another abelian group $U(1)_X$ without violating either $U(1)$ symmetry. This term can arise in higher order of perturbation theory as a result of mixing induced by loops of fermions with non-degenerate masses. Thus, it is permissible to take any linear combination of Q_χ and Q_ψ and add to it a term proportional to $Y_W = 2I_{3R} + Y_L + Y_R$ in order to try to cancel out couplings to conventional leptons. By this means one can construct a Z' that is particularly elusive in direct searches but whose effects can be manifested in other ways [5, 6].

The assignments of quantum numbers to left-handed members of the **27**-plet of E_6 are shown in Table 1. The (unnormalized) charge Q' is defined as that linear combination of I_{3R}, Y_L, and Y_R for which $Q'(e_L^-) = Q'(\nu_{eL}) = Q'(e^+) = 0$. Adopting a convenient normalization, we find

$$Q' = (Q_\eta + Y_W)/5 = I_{3R} - Y_L + (1/2)Y_R \quad . \tag{4}$$

Values of this charge are also shown in Table 1.

It is amusing that the charges Q' are just a re-arranged version of the electromagnetic charges in the **27**-plet. One passes from Q in Eq. (1) to Q' in Eq. (4) by the substitution $I_{3L} + (1/2)Y_L \to -Y_L$, which amounts to a Weyl reflection interchanging the second and third components of $SU(3)_L$.

The values of Q' in Table 1 vanish for the left-handed exotic lepton E^- and its left-handed neutrino state ν_E as well as for the conventional leptons. However, they are largest in magnitude for all the other exotic leptons: the "right-handed neutrino" whose left-handed state is N_e^c, the states E^+ and ν_E^c, and the otherwise elusive n (whose charge and weak hypercharge both vanish, so it doesn't couple to the photon *or* the standard Z).

A complete set of fermions in the **27** must remain light in order to cancel the anomaly in the charge Q' [7]. Thus, it makes sense to imagine that a Z' coupling to this charge will have branching ratios given by comparing the square of each charge in Table 1 to the sum of their squares. Summing over left-handed particles and their charge-conjugates, and taking account of color factors for quarks, we obtain the results in Table 2. Only single entries are shown in the second column for the Majorana particles N_e^c and n. If three full **27**-plets are sufficiently light, the branching ratios in Table 2 should be divided by 3 to get each net branching ratio (shown in the last column). All branching ratios are reduced further if one must take account of decays to light superpartners [16].

Also shown in Table 2 are forward-backward asymmetries for the quark sub-processes $u\bar{u} \to f\bar{f}$ at the Z' pole. (Since d quarks have the same magnitude of

2

Table 1: Assignment of quantum numbers to left-handed members of the **27**-plet of E_6.

$(SO(10), SU(5))$	Q_η	State	Q	I_{3L}	I_{3R}	Y_L	Y_R	Q'
$(\mathbf{16}, \mathbf{5}^*)$	1	d^c	1/3	0	1/2	0	$-1/3$	1/3
		e^-	-1	$-1/2$	0	$-1/3$	$-2/3$	0
		ν_e	0	1/2	0	$-1/3$	$-2/3$	0
$(\mathbf{16}, \mathbf{10})$	-2	u	2/3	1/2	0	1/3	0	$-1/3$
		d	$-1/3$	1/2	0	1/3	0	$-1/3$
		u^c	$-2/3$	0	$-1/2$	0	$-1/3$	$-2/3$
		e^+	1	0	1/2	2/3	1/3	0
$(\mathbf{16}, \mathbf{1})$	-5	N_e^c	0	0	$-1/2$	2/3	1/3	-1
$(\mathbf{10}, \mathbf{5}^*)$	1	h^c	1/3	0	0	0	2/3	1/3
		E^-	-1	$-1/2$	$-1/2$	$-1/3$	1/3	0
		ν_E	0	1/2	$-1/2$	$-1/3$	1/3	0
$(\mathbf{10}, \mathbf{5})$	4	h	$-1/3$	0	0	$-2/3$	0	2/3
		E^+	1	1/2	1/2	$-1/3$	1/3	1
		ν_E^c	0	$-1/2$	1/2	$-1/3$	1/3	1
$(\mathbf{1}, \mathbf{1})$	-5	n	0	0	0	2/3	$-2/3$	-1

left- and right-handed Q' charges, all forward-backward asymmetries for $d\bar{d} \to f\bar{f}$ vanish at the Z' pole.) These asymmetries may be expressed as

$$A_{FB} = \frac{3}{4} \frac{[Q(u)^2 - Q(u^c)^2][Q(f)^2 - Q(f^c)^2]}{[Q(u)^2 + Q(u^c)^2][Q(f)^2 + Q(f^c)^2]} \qquad (5)$$

We have adopted the conventions that N_e, h, E^-, ν_E, and n correspond to fermions f. Table 2 has a few interesting features.

(1) In contrast to the decays of a standard Z, for which the branching ratio to $d\bar{d}$ exceeds that to $u\bar{u}$, the Z' considered here prefers to decay to $u\bar{u}$ by a factor of 2.5. If such a Z' is heavier than $2m_t$, it can be an additional source of top quark pairs beyond standard QCD. A momentum-weighted jet charge analysis [17] would be able to determine whether jets produced at high transverse momenta could be due to Z' decays in which up-type species predominated.

(2) The decays to h (an exotic isosinglet quark with charge $-1/3$) are quite prominent. If this quark decays via flavor-changing neutral currents to other charge $-1/3$ quarks, a signal of Z' production might include unusual events containing ordinary down-type quarks (such as b quarks), photons, and virtual or real Z's.

(3) The decays to the exotic leptons N_e^c, E, ν_E, and n make up half of all Z' decays to a given family. One should then expect to see unusual decay products, which might consist of leptons, photons, and virtual Z's if flavor-changing neutral currents dominate the decays of the exotic leptons.

(4) The prominence of up-type quark couplings to Z' and the presence of substantial forward-backward asymmetries in $u\bar{u} \to f\bar{f}$ imply that the process

Table 2: Branching ratios for a Z' coupling to the charge Q' into various members of a single family in the **27**-plet of E_6.

State f	Squared charge	Branching ratio	Branching ratio/3 (%)	$A_{FB}(u\bar{u} \to Z' \to f\bar{f})$
d	$(1+1)/3$	$1/12$	2.8	0
u	$(1+4)/3$	$5/24$	6.9	0.27
N_e^c	1	$1/8$	4.2	0.45
h	$(4+1)/3$	$5/24$	6.9	-0.27
E	$0+1$	$1/8$	4.2	0.45
ν_E	$0+1$	$1/8$	4.2	0.45
n	1	$1/8$	4.2	-0.45
Total	8	1	33.3	

$\bar{p}p \to Z' \to f\bar{f}$ is likely to produce all the states f in Table 2 except standard down-type quarks with substantial forward-backward asymmetries. Such asymmetries could be an early signal that new physics is appearing through the intervention of a chiral interaction rather than through QCD, which is left-right symmetric.

Typical searches for new Z' states produced and decaying like standard Z's have reached mass limits of about 650 GeV/c^2 when one combines the CDF e^+e^- and $\mu^+\mu^-$ data in samples of about 70 pb^{-1} [4]. The full sample from CDF, and the inclusion of D0 results, can be expected to more than double the amount of data available, leading to lower limits closer to 700 GeV/c^2. For Z''s coupling only to U(1) factors, for which the square of the coupling is about half of that for electroweak SU(2), one should reduce the expected production cross sections by about a factor of 2, bringing the anticipated limits back down to 650 GeV/c^2 for final states identified with the same efficiency and branching ratio (3.4%) as in $Z \to e^+e^-$ decays. The Z' discussed here has branching ratios to each species of exotic leptons in excess of this figure, but detection efficiencies are hard to anticipate without predictions for specific decay chains. Indeed, to some extent it is misleading even to identify the exotic states in E_6 as quarks and leptons before we know what selection rules govern their decays. The answer to such questions depends on symmetry-breaking schemes which we have not yet explored.

Acknowledgments

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