Prominent Decay Modes of a Leptophobic $Z'$

Jonathan L. Rosner

CERN, 1211-CH Geneva 23, Switzerland

Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637 USA

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 $uar{u} \rightarrow Z' \rightarrow far{f}$ channels when $f$ is a standard up-type quark, an exotic down-type quark, or an exotic lepton.

PACS codes: 14.70.Pw, 12.60.Cn, 12.10.Dm, 13.38.Dg

1To be published in Physics Letters B.

2Permanent address.
It was proposed some time ago [1] that searches for new neutral gauge bosons $Z'$, traditionally pursued at the highest energies using the reaction $\bar{p}p \rightarrow Z' + \ldots \rightarrow (e^+e^- + \ldots$ or $\mu^+\mu^- + \ldots)$ [2], 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 recent specific motivations (see, e.g., Refs. [3–12]) which seek to explain an excess branching ratio $B(Z \rightarrow b\bar{b})$ [13] and an excess of jets produced at high transverse momenta in $\bar{p}p$ collisions [14] with respect to standard-model predictions.

Although a leptophobic $Z'$ might appear artificial from the standpoint of unified theories of the electroweak and strong interactions, such a state can be constructed using the U(1) charges available within the group $E_6$ [1, 6]. 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 $Z$. In contrast to Refs. [11], [12], and several others mentioned in Ref. [8], we consider for simplicity only a model with family-independent couplings.

Candidates for groups unifying color SU(3) with electroweak SU(2) × U(1) include SU(5), SO(10), and $E_6$. The SU(5) group [15] is the smallest with which this unification can be achieved; the familiar left-handed fermions belong to a $5^* + 10$-dimensional reducible representation. With the addition of a right-handed neutrino, these two representations may be combined in a single 16-dimensional spinor of SO(10) [16]. This, in turn, is contained in a 27-dimensional representation of $E_6$, which is a group often encountered in superstring theories [17] but whose possibilities for strong-electroweak unification were explored before the superstring era [18]. In addition to the SO(10) 16-plet, the 27 of $E_6$ contains representations of (SO(10), SU(5)) with dimensions $(10, 5^*+5)$ and $(1, 1)$.

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)$_\psi$ [19, 20, 21]. One particular combination of these two U(1)’s is frequently discussed in the context of superstring theories [17] and is called U(1)$_\eta$. (More details on searches for extra Z’s, including $Z_\eta$, may be found in Refs. [22].) The leptophobic $Z'$ constructed in Ref. [6] 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 $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R \rightarrow SU(3)_C \times SU(2)_L \times U(1)_L \times SU(2)_R \times U(1)_R$ [17]. The 27-plet of $E_6$ consists of $(3,3,1) + (3^*,1,3^*) + (1,3^*,3)$ 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

$$Q = I_{3L} + \frac{Y_W}{2} = I_{3L} + I_{3R} + \frac{Y_L + Y_R}{2}. \quad (1)$$
Unnormalized charges corresponding to $U(1)_\chi$ and $U(1)_\psi$ may be expressed \[17\] as
\[Q_\chi = 4I_{3R} - 3(Y_L + Y_R), \quad Q_\psi = 3(Y_R - Y_L),\] (2)
while a charge corresponding to $U(1)_\eta$ is a linear combination of these \[17\]:
\[Q_\eta = 3I_{3R} - 6Y_L + (3/2)Y_R.\] (3)

The authors of Ref. \[6\] note that it is possible to include in the Lagrangian a term mixing the field strength $B_{\mu\nu}$ of weak hypercharge $U(1)_Y$ with the field strength $X_{\mu\nu}$ of another abelian group $U(1)_\chi$ 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 $Q_\chi$ and $Q_\psi$ 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 \[13, 14\].

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

Values of this charge are also shown in Table 1. The decoupling from leptons of the linear combination (4) was noted in Refs. \[1\].

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 $I_{3L} + (1/2)Y_L \rightarrow -Y_L$, which amounts to a Weyl reflection interchanging the first ($u$) and third ($h$) 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 $\nu_E$ 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 $N^c_e$, the states $E^+$ and $\nu^c_E$, 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 $Q'$ \[9\]. 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 $N^c_e$ 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 \[23\].
Table 1: Assignment of quantum numbers to left-handed members of the $27$-plet of $E_6$.

| $(\text{SO}(10), \text{SU}(5))$ | $Q_\eta$ | State | $Q$ | $I_{3L}$ | $I_{3R}$ | $Y_L$ | $Y_R$ | $Q'$ |
|-----------------------------|---------|-------|-----|---------|---------|-------|-------|------|
| $(16, 5^*)$ | 1       | $d^c$ | 1/3 | 0       | 1/2     | 0     | $-1/3$ | 1/3  |
|                  |         | $e^-$ | $-1$ | $-1/2$  | 0       | $-1/3$ | $-2/3$ | 0    |
|                  |         | $\nu_e$ | 0   | 1/2     | 0       | $-1/3$ | $-2/3$ | 0    |
| $(16, 10)$       | $-2$    | $u$   | 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    |
| $(16, 1)$        | $-5$    | $N_e^c$ | 0   | 0       | $-1/2$  | 2/3   | 1/3   | $-1$ |
| $(10, 5^*)$      | 1       | $h^c$ | 1/3 | 0       | 0       | 0     | 2/3   | 1/3  |
|                  |         | $E^-$ | $-1$ | $-1/2$  | $-1/2$  | $-1/3$ | 1/3   | 0    |
|                  |         | $\nu_E$ | 0   | 1/2     | $-1/2$  | $-1/3$ | 1/3   | 0    |
| $(10, 5)$        | $4$     | $h$   | $-1/3$ | 0       | 0       | $-2/3$ | 0     | 2/3  |
|                  |         | $E^+$ | 1    | 1/2     | 1/2     | $-1/3$ | 1/3   | 1    |
|                  |         | $\nu_{E^c}$ | 0   | $-1/2$  | 1/2     | $-1/3$ | 1/3   | 1    |
| $(1, 1)$         | $-5$    | $n$   | 0    | 0       | 0       | 2/3   | $-2/3$ | $-1$ |

Also shown in Table 2 are forward-backward asymmetries for the quark subprocesses $u\bar{u} \rightarrow f\bar{f}$ at the $Z'$ pole. (Since $d$ quarks have the same magnitude of left- and right-handed $Q'$ charges, all forward-backward asymmetries for $d\bar{d} \rightarrow f\bar{f}$ vanish at the $Z'$ pole.) These asymmetries may be expressed as

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

(5)

We have adopted the conventions that $N_e, h, E^-, \nu_E,$ 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 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 $N_e^c, E, \nu_E,$ and $n$ make up half of all $Z'$ decays to a given family. One should then expect to see unusual decay products consisting of leptons, photons, and virtual $Z$'s if flavor-changing neutral currents


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 | Squared charge | Branching ratio/3 (%) | $A_{FB}(\bar{u}u \rightarrow Z' \rightarrow f \bar{f})$ |
|-------|----------------|-----------------------|----------------------------------|
| $d$   | $(1 + 1)/3$    | 1/12                  | 2.8                              |
| $u$   | $(1 + 4)/3$    | 5/24                  | 0.27                             |
| $N^c_e$ | 1             | 1/8                   | 4.2                              |
| $h$   | $(4 + 1)/3$    | 5/24                  | 6.9                              |
| $E$   | 0 + 1          | 1/8                   | 4.2                              |
| $\nu_E$ | 0 + 1        | 1/8                   | 4.2                              |
| $n$   | 1              | 1/8                   | 4.2                              |
| Total | 8              | 1                     | 33.3                             |

dominate the decays of the exotic leptons. In principle, by a several-step mode whose details would be dependent on the symmetry-breaking scheme giving rise to masses, a process such as $Z' \rightarrow E^+E^-$ or $Z' \rightarrow \nu_E\bar{\nu}_E$ could give rise to the unusual event $\bar{p} + p \rightarrow e^+e^-\gamma\gamma + \text{(missing transverse energy)}$ seen by CDF [25].

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

[Note added: After this work was completed we became aware of Ref. [26], which proposes searching for $Z' \rightarrow (W^\pm \text{ or } Z) + \text{ scalar}$. In our notation, the rates for these decays involve factors $[Q'(q_L) + Q'(u^c_L)][Q'(q_L) + Q'(d^c_L)]$, where...
\[ q_L \equiv (u_L, d_L), \] which vanish for our choice of charges (possibly disfavored if one seeks a solution to the \( R_b \) problem compatible with other phenomenology \[\text{[7].}\]

**Acknowledgments**

I thank the Aspen Center for Physics and the CERN and Fermilab Theory Groups for their hospitality during parts of this study; H. Frisch, A. K. Grant, M. L. Mangano, and J. Steinberger for fruitful discussions; and A. Faraggi, P. Frampton, and J. L. Lopez for calling my attention to Refs. \[\text{[1]}, \text{[2]}, \text{and [3].} \] This work was supported in part by the United States Department of Energy under Contract No. DE FG02 90ER40560.

**References**

[1] F. del Aguila, G. Blair, M. Daniel, and G. G. Ross, Nucl. Phys. **B283** (1987) 50; F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B284** (1987) 530; **287** (1987) 419.

[2] CDF Collaboration, F. Abe et al., Phys. Rev. D **51** (1995) 949; T. Kamon, Fermilab report FERMILAB-CONF-96-106-E, \[\text{hep-ex/9605006.} \] presented at XXXI Rencontre de Moriond: QCD and High-energy Hadronic Interactions, 23 – 30 March, 1996.

[3] G. Altarelli, N. di Bartolomeo, F. Feruglio, R. Gatto, and M. L. Mangano, CERN report CERN-TH/96-29, \[\text{hep-ph/9601324.} \]

[4] P. Chiappetta, J. Layssac, F. M. Renard, and C. Verzegnassi, Montpelier Univ. report PM-96-05, \[\text{hep-ph/9601308.} \]

[5] P. Bamert, C. P. Burgess, J. M. Cline, D. London, and E. Nardi, McGill Univ. report McGill 96-04, \[\text{hep-ph/9602438.} \]

[6] K. S. Babu, C. Kolda, and J. March-Russell, Institute for Advanced Study report IASSNS-HEP-96/20, \[\text{hep-ph/9603212.} \] C. Kolda, Institute for Advanced Study report IASSNS-HEP-96/65, \[\text{hep-ph/9606396.} \] talk given at the IV International Conference on Supersymmetry (SUSY-96), College Park, MD, May 29 – June 1, 1996.

[7] K. Agashe, M. Graesser, I. Hinchliffe, and M. Suzuki, Lawrence Berkeley National Laboratory report LBL-38569, \[\text{hep-ph/9604266.} \]

[8] V. Barger, K. Cheung, and P. Langacker, Univ. of Wisconsin report MADPH-96-936, \[\text{hep-ph/9604298.} \]

[9] T. Gehrmann and W. J. Stirling, Durham Univ. report DTP/96/24, \[\text{hep-ph/9603380.} \] M. Heyssler, Durham Univ. report DTP/96/42, \[\text{hep-ph/9605403.} \]
[10] A. E. Faraggi and M. Masip, Univ. of Florida report UFIFT-HEP-96-11, hep-ph/9604302.

[11] P. H. Frampton, M. B. Wise, and B. D. Wright, Univ. of North Carolina report IFP-722-UNC, hep-ph/9604260.

[12] J. L. Lopez and D. V. Nanopoulos, Rice Univ. report DOE/ER/40717-27, hep-ph/9605359; J. L. Lopez, Rice Univ. report DOE/ER/40717-30, hep-ph/9607231, to appear in Proceedings of the Fourth International Conference on Supersymmetry (SUSY-96), College Park, MD, May 29 – June 1, 1996.

[13] ALEPH, DELPHI, L3, and OPAL Collaborations and the LEP Electroweak Working Group, CERN report CERN-PPE/95-172, November 1995, contributed to the 1995 International Europhysics Conference on High Energy Physics, Brussels, Belgium, 27 July – 2 August 1995, and to the 17th International Symposium on Lepton-Photon Interactions, Beijing, China, 10 – 15 August 1995; ALEPH, DELPHI, L3, and OPAL Collaborations, CERN report CERN-PPE/96-017, February 1996, submitted to Nucl. Instr. Meth.

[14] CDF Collaboration, F. Abe et al., Fermilab-Pub-96/020-E, January, 1996, submitted to Phys. Rev. Letters.

[15] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32 (1974) 438.

[16] H. Georgi in Proceedings of the 1974 Williamsburg DPF Meeting, ed. by C. E. Carlson (New York, AIP, 1975) p. 575; H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93 (1975) 193.

[17] E. Witten, Nucl. Phys. B258 (1985) 75; E. Cohen, J. Ellis, K. Enqvist, and D. V. Nanopoulos, Phys. Lett. 165B (1985) 76; J. L. Rosner, Comments on Nucl. Part. Phys. 15 (1986) 195.

[18] F. Gürsey, P. Ramond, and P. Sikivie, Phys. Lett. 60B (1976) 177.

[19] R. W. Robinett, Phys. Rev. D 26 (1982) 2388; R. W. Robinett and J. L. Rosner, Phys. Rev. D 25 (1982) 3036; 26 (1982) 2396.

[20] P. G. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. D 30 (1984) 1470.

[21] D. London and J. L. Rosner, Phys. Rev. D 34 (1986) 1530.

[22] L. S. Durkin and P. Langacker, Phys. Lett. 166B (1986) 436; U. Amaldi et al., Phys. Rev. D 36 (1987) 1385; F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. B287 (1987) 457; J. L. Hewett and T. G. Rizzo, Phys. Rep. 183 (1989) 193; P. Langacker and M. Luo, Phys. Rev. D 45 (1992) 278; P. Langacker, in Precision Tests of the Standard Model, edited by P. Langacker (World Scientific, Singapore, 1995), p. 883; M. Cvetič and S. Godfrey, in Electro-weak Symmetry Breaking and Beyond the Standard Model, edited by
T. Barklow, S. Dawson, H. Haber, and J. Siegrist (World Scientific, Singapore, 1995), and references therein; M. Cvetić and P. Langacker, Institute for Advanced Study report IASSNS-HEP-95/90, hep-ph/9511378 (unpublished).

[23] J. F. Gunion et al., Int. J. Mod. Phys. A 2 (1987) 1199; S. Nandi, Phys. Lett. B 197 (1987) 144; J. L. Hewett and T. G. Rizzo, Ref. [22].

[24] R. D. Field and R. P. Feynman, Nucl. Phys. B136 (1978) 1. For recent applications see, e.g., SLD Collaboration, K. Abe et al., Phys. Rev. Lett. 74 (1995) 2890; ALEPH Collaboration, D. Buskulic et al., Phys. Lett. B 356 (1995) 409; DELPHI Collaboration, P. Abreu et al., Zeit. Phys. C 65 (1995) 569; OPAL Collaboration, R. Akers et al., Zeit. Phys. C 67 (1995) 365.

[25] CDF Collaboration, F. Abe et al., presented by S. Park, in Proceedings of the 10th Topical Workshop on Proton-Antiproton Collider Physics, Fermilab, May 9–13, 1995, AIP Conference Proceedings 357, edited by R. Raja and J. Yoh, (AIP, Woodbury, NY, 1996), p. 62.

[26] H. Georgi and S. L. Glashow, Harvard University report HUTP-96/A024, hep-ph/9607202.