PHYSICAL REVIEW D VOLUME 55, NUMBER 5 1 MARCH 1997

E_6 interpretation of an $e^+e^-\gamma\gamma\not{E}_T$ event

Jonathan L. Rosner
CERN, 1211-CH Geneva 23, Switzerland
and Enrico Fermi Institute and Department of Physics,
*University of Chicago, Chicago, Illinois 60637**

(Received 26 August 1996)

The lowest-dimensional representation of the group E_6 contains both the standard quarks and leptons and a set of exotic quarks and leptons whose decays can involve a series of chains ending in radiative decay of one light neutrino species into another. An example is given based on the decomposition $E_6 \rightarrow SU(2)_I \times SU(6)$, where $SU(2)_I$ is an ''inert'' subgroup whose gauge bosons $W_I^{(\pm)}$ and Z_I are all electromagnetically neutral, while SU(6) contains the conventional SU(5) grand-unified group. The possibility is explored that such a chain is responsible for an event observed by the Collider Detector at Fermilab involving the production in proton-antiproton collisions at $E_{\mathrm{c.m.}}=1.8$ TeV of an electron-positron pair, two photons, and missing energy ($e^+e^-\gamma\gamma\not{E}_T$). [S0556-2821(97)05705-6]

PACS number(s): 14.70.Pw, 12.10.Dm, 12.60.Cn, 13.38.Dg

I. INTRODUCTION

The ''grand unification'' of strong and electroweak interactions in a larger symmetry, and the identification of quarks and leptons as objects related to one another under this symmetry, involve such groups as SU(5) [1], SO(10) [2], and E_6 [3]. We briefly recall some properties of each group.

Within SU(5) a specific choice of representations ($\mathbf{5}^*+\mathbf{10}$) is required for the left-handed fermions in order to accommodate the known states and to eliminate anomalies. This choice is automatic if left-handed fermions are assigned to the 16-dimensional spinor multiplet of SO(10); the additional state is a right-handed neutrino. Anomalies are not present in SO(10), as long as matter belongs to complete multiplets.

The lowest-dimensional representation (**27**) of the group E_6 contains the **16** of SO(10), as well as ten- and one-dimensional (''exotic'') representations of SO(10). There has been some interest in E_6 as a result of its appearance in certain versions of superstring theories [4,5].

In the present article we discuss some properties of a decomposition [6,7] of E_6 into a subgroup $SU(2)_I\times SU(6)$, where the subscript I stands for ''inert.'' The SU(6) contains the conventional grand-unified group SU(5) and an additional U(1) factor which may be denoted $U(1)_{51}$. The gauge bosons of $SU(2)_I\times U(1)_{51}$ are all electromagnetically neutral. These gauge bosons may mediate some interesting processes in hadronic collisions, electron-positron annihilations, and e^-p reactions.

We have been stimulated to recall features of the present E_6 decomposition by the Collider Detector at Fermilab (CDF) Collaboration's report [8] of an event with an electron-positron pair, two photons, and missing energy ($e^+e^-\gamma\gamma\not{E}_T$), produced in proton-antiproton collisions at $E_{\mathrm{c.m.}}=1.8$ TeV. Alternative interpretations of this event have appeared within the context of supersymmetry [9] and in one nonsupersymmetric model [10]. There is still a need for extensive discussions of standard-model backgrounds and alternative experimental interpretations for this event, such as multiple interactions, radiative production of W pairs, effects of cracks in the detector, quality of lepton identification, and so on.

While we are aware of the dangers of speculations based on a single event, the possibility that one is seeing evidence for an extended gauge structure (such as occurs in E_6) is sufficiently appealing and predictive that it is worth considering at present, even though many of the predictions have been in the literature for some time. Our picture will be explicitly nonsupersymmetric and is meant in part to illustrate the pitfalls of too hasty a conclusion that a given class of events has proved the validity of low-energy supersymmetry.

In Sec. II we recall some of the necessary E_6 group theory. Implications for the CDF $e^+e^-\gamma\gamma\not{E}_T$ event and others produced in hadron colliders are treated in Sec. III. Some signatures in other machines are noted in Sec. IV, while Sec. V concludes.

II. DECOMPOSITION

A. Multiplet structure

The **27** of E_6 corresponding to the first family of left-handed quarks and leptons may be decomposed in the following manner under $SU(2)_I\times SU(6)$:

$$(\mathbf{2}_I,\mathbf{6}^*)_L=\begin{bmatrix} \overline{h_1} & \overline{d_1} \\ \overline{h_2} & \overline{d_2} \\ \overline{h_3} & \overline{d_3} \\ \nu_E & \nu_e \\ E^- & e^- \\ \overline{N_e} & n_e \end{bmatrix}, \qquad (1)$$

---

*Permanent address.

$$(\mathbf{1}_I,\mathbf{15})_L=\begin{bmatrix} 0 & \overline{u_3} & -\overline{u_2} & d_1 & u_1 & h_1 \\ -\overline{u_3} & 0 & \overline{u_1} & d_2 & u_2 & h_2 \\ \overline{u_2} & -\overline{u_1} & 0 & d_3 & u_3 & h_3 \\ -d_1 & -d_2 & -d_3 & 0 & e^+ & \overline{N_E} \\ -u_1 & -u_2 & -u_3 & -e^+ & 0 & E^+ \\ -h_1 & -h_2 & -h_3 & -\overline{N_E} & -E^+ & 0 \end{bmatrix}.$$

Similar decompositions hold for the second and third quark-lepton families.

Although the exotic fermions in E_6 have been discussed previously (see, e.g., [3] and [13]), we review them briefly. We mention the properties of the left-handed states; those of the right-handed states may be obtained via CP conjugation.

h is a weak-isosinglet quark with charge $-1/3$.

ν_E and E^- are members of a weak isodoublet; so are E^+ and $\overline{N}_E$. We write $\overline{N}_E$ rather than $\overline{\nu}_E$ to stress the possibility that ν_E and $\overline{N}_E$ may be two distinct Majorana neutrinos rather than components of a single Dirac neutrino.

$\overline{N}_e$ is the left-handed antiparticle (the CP conjugate) of the right-handed neutrino N_e. As in the previous case, ν_e and $\overline{N}_e$ may be two distinct Majorana neutrinos rather than components of a single Dirac neutrino.

n_e is a Majorana neutrino which is a singlet under both left-handed and right-handed SU(2).

All the exotic fermions listed above except n_e may be assigned to a **10**-plet of SO(10) under $E_6 \to$ SO(10)×U(1). The n_e may be assigned to a singlet of SO(10). An alternative assignment to SO(10) multiplets is generated by interchanging states in the two columns of $(\mathbf{2}_I,\mathbf{6}^*)_L$ [11,12].

With the above descriptions it should be clear how subgroups of SU(6), such as color SU(3) and weak (left-handed) SU(2), act on the multiplets in Eq. (1). For example, in the multiplet $(\mathbf{2}_I,\mathbf{6}^*)_L$, color SU(3) acts on the first three rows, while $SU(2)_L$ acts on the fourth and fifth rows. The conventional grand-unified SU(5) acts on the first five rows. The behavior of SU(6) subgroups acting on the **15** is best seen by constructing it as the antisymmetric product of two **6**'s. Thus, $(u_i,d_i)_L$ $(i=1,2,3)$ and $(E^+,\overline{N}_E)$ form $SU(2)_L$ doublets.

B. U(1) charges in SU(6) → SU(5) × U(1)

The simplest pattern of subsequent breakdown after $E_6 \to SU(2)_I \times SU(6)$ is SU(6) $\to SU(5)\times U(1)_{51}$, where SU(5) is the conventional grand-unified group and $U(1)_{51}$ denotes an extra U(1) factor. Adopting integral values for the charges Q_{51} of this U(1), we may decompose the $\mathbf{6}^*$ of SU(6) in Eq. (1) as $\mathbf{6}^*=\mathbf{5}^*_1+\mathbf{1}_{-5}$ and, since a **15** is the antisymmetric product of two **6**'s, we find $\mathbf{15}=\mathbf{10}_{-2}+\mathbf{5}_4$. Here, the boldface numbers on the right denote the dimension of the SU(5) representation, while the subscripts denote the U(1) charges Q_{51}.

C. Fermion masses

We seek a pattern of mass splittings consistent with the hypothesis that all the exotic fermions which can couple to the photon and Z have masses large enough that they will not have been produced in the tens of millions of Z decays observed at the CERN LEP electron-positron collider and in the smaller amount of data collected at higher energies. The mass splittings will be implemented by means of Higgs bosons belonging to a **27**-plet of E_6, through the E_6-invariant trilinear coupling of three **27**'s.

TABLE I. Higgs bosons belonging to the **27**-plet of E_6 and their transformation properties under some of its subgroups.

Boson	I_{3L}	I_{3I}	Q_{51}	What its VEV does
$\tilde{\nu}_E$	1/2	1/2	1	Gives d,e Dirac mass
$\tilde{\nu}_e$	1/2	$-1/2$	1	Mixes exotics, nonexotics
$\tilde{\overline{N}}_e$	0	1/2	-5	Mixes exotics, nonexotics
$\tilde{n}_e$	0	$-1/2$	-5	Gives h,ν_E,E Dirac mass
$\tilde{\overline{N}}_E$	$-1/2$	0	4	Gives u,ν Dirac mass

The similarity of Higgs and fermion representations is a feature which makes E_6 particularly appealing in supersymmetric theories. Thus, without making any necessary claims of supersymmetry, we will use a tilde to denote a scalar particle transforming in the same manner under E_6 or $SU(2)_I\times SU(6)$ as the neutral states in Eq. (1). The Higgs bosons, their transformation properties, and the effects of their vacuum expectation values (VEV's) are listed in Table I.

The ''standard'' Higgs bosons in the present notation are $\tilde{\nu}_E$ and $\tilde{\overline{N}}_E$. Sufficiently large Dirac masses for the exotic fermions h, ν_E, and E may be generated by a VEV of the boson $\tilde{n}_e$. Such a Dirac mass term couples ν_E with $\overline{N}_E$. Exotic fermions may be mixed with nonexotic ones via VEV's of the two remaining Higgs bosons $\tilde{\nu}_e$ and $\tilde{\overline{N}}_e$. These VEV's may be very small if some selection rule forbids the mixing of exotic and nonexotic fermions. Thus, a reasonable hierarchy for VEV's would be

$$\langle\tilde{n}_e\rangle \simeq 1\ \text{TeV} \gg (\langle\tilde{\nu}_E\rangle,\langle\tilde{\overline{N}}_E\rangle)=O(v)\gg(\langle\tilde{\nu}_e\rangle,\langle\tilde{\overline{N}}_e\rangle), \quad (2)$$

where $v=246$ GeV$=2^{-1/4}G_F^{-1/2}$ characterizes the electroweak-breaking scale.

As mentioned in Ref. [14], one can describe all fermion masses satisfactorily using the pattern suggested by Table I and employing E_6-invariant couplings, with the exception of neutrinos. Since Dirac masses for up-type quarks and neutrinos both arise through the VEV of the Higgs boson $\tilde{\overline{N}}_E$, one needs (i) to introduce some additional source of a large Majorana mass for N_e (see, e.g., [15]), thereby causing ordinary neutrinos to have very small Majorana masses [16], (ii) to provide an additional singlet of E_6 with which N_e can form a Dirac mass [11], or (iii) to explicitly forbid the trilinear coupling between a pair of fermions transforming as $(\mathbf{2}_I,\mathbf{6}^*)_L$ and a boson transforming as $(\mathbf{1}_I,\mathbf{15})_L$. We shall adopt the last point of view, since a fairly light N_e will play a likely role in our explanation of the $e^+e^-\gamma\gamma\not{E}_T$ event. We regard this as the least satisfactory feature of the present model.

There appears to be no phenomenological need to generate a mass for n_e, and no source of such a mass except through the couplings $n_e\nu_E\tilde{\overline{N}}_E$ or $n_e\overline{N}_E\tilde{\nu}_E$ (whose effects could be well overwhelmed by a Dirac mass involving the pairing of $\bar{N}_E$ with ν_E). Thus, *an appealing candidate for a light state is the state* n_e, as has been pointed out elsewhere [12,17–19].

The Dirac masses of the exotic fermions h, E, and ν_E could be of any values high enough to evade bounds associated with Z decays and with more recent higher-energy electron-positron collision experiments at the CERN e^+e^- collider LEP. As in the case of b and τ, masses which start out identical at very small distance scales will evolve at larger distances as a result of differing gauge interactions in such a way that one will expect exotic quarks to be more massive (perhaps by roughly the factor m_b/m_τ) than exotic leptons.

D. Exotic gauge boson masses and couplings

We assume that in the breakdowns $E_6 \to SU(2)_I \times SU(6)$ and $SU(5) \to SU(3)_c \times SU(2)_L \times U(1)_Y$ (where Y is the standard weak hypercharge), the gauge bosons corresponding to the broken symmetries obtain superheavy masses. Thus, we are left with the gauge bosons of $SU(2)_I \times U(1)_{51}$ to discuss.

In the hierarchy (2), the largest VEV is acquired by a doublet of $SU(2)_I$ with nonzero charge Q_{51}. This situation is very close to that of the Weinberg-Salam model. If this were the only source of $SU(2)_I \times U(1)_{51}$ breaking, we would have three massive bosons (two lighter than the third) and a massless boson. For simplicity, we assume instead that the $U(1)_{51}$ factor is broken at a high mass scale by some other mechanism and that we have only to deal with $SU(2)_I$. In that case we will have a theory equivalent to the Weinberg-Salam model with $\theta = 0$, and there will be three electromagnetically neutral bosons, each with mass of several hundred GeV. [A lower limit of order 10^5 GeV on the scale of $SU(2)_I$ breaking was obtained in [20] with specific model-dependent assumptions and does not apply here.]

We use the notation $W_I^{(\pm)}$ for two of the neutral bosons to denote the fact that they change I_{3I} by ± 1 unit. The third boson (which couples to I_{3I} but does not change it) will be denoted by Z_I. The masses of the three bosons will be

$$M_I = g_I V/2, \quad V^2 \equiv \sum_i \langle \tilde{n}_i \rangle^2, \tag{3}$$

where g_I is the $SU(2)_I$ coupling constant [probably no stronger than the standard $SU(2)_L$ electroweak coupling constant] and the sum is over all families of Higgs bosons transforming as $\tilde{n}_e$. V is likely to be a number of order 1 TeV if the exotic fermions discussed above are to be responsible for signals observed in present collider experiments. The possibility of a second Z' within E_6, if one does not choose to break the $U(1)_{51}$ symmetry at some high mass scale, should be kept in mind.

III. EFFECTS OF W_I AND Z_I AT HADRON COLLIDERS

Some features of exotic fermion production and decay via gauge interactions mediated by W_I and Z_I were discussed in [7]. We concentrate in this section on production via $d\bar{d}$ collisions and decay via W_I exchange.

A. Production and decay of Z_I

The states coupling to Z_I are the members of the $(\mathbf{2}_I, \mathbf{6}^*)_L$ in Eq. (1). Each state couples with equal strength, since each has $I_{3I} = \pm 1/2$. The Z_I can be produced in the direct channel in electron-positron collisions, or it can be produced in hadronic collisions via the $d\bar{d} \to Z_I$ subprocess. Since d quarks are softer than u quarks in a proton (and there are fewer of them), the production of Z_I at the Fermilab Tevatron (involving proton-antiproton collisions) will be more difficult than that of most other Z' states within E_6 [7,21]. One can see this feature in the relatively weak limits placed on Z_I production in present Tevatron data [22]. A Z_I of 511 GeV (corresponding to the highest-mass e^+e^- pair observed by CDF) is a possible candidate for such a state.

The branching ratios for Z_I decay can be deduced from the states with masses below $M(Z_I)/2$ with $I_{3I} = \pm 1/2$, as in Eq. (1). Thus, for three such families, the branching ratio to e^+e^- would be $1/36 \simeq 3\%$, not very different from that of a standard Z. The presence of superpartners in final states would lower branching ratios further [23].

The subprocess $d\bar{d} \to Z_I \to e^-e^+$ is characterized by a maximal angular asymmetry (i.e., $A_{FB} = -3/4$) in the backward direction [24], as one can see from the couplings in Eq. (1). This is in contrast with the large forward asymmetry $A_{\mathrm{FB}} \simeq 0.6$ expected [24] and observed [25] for the subprocesses ($u\bar{u}$ or $d\bar{d}$) $\to (\gamma^*, Z^*) \to e^-e^+$ in the standard model for e^-e^+ masses in the Drell-Yan continuum well above the Z.

The Z_I can decay to pairs of exotic fermions such as $h\bar{h}$, $\nu_E\bar{\nu}_E$, E^-E^+, $\bar{N}_e N_e$, and $n_e\bar{n}_e$. It thus acts as a gateway from the conventional world to exotic matter, allowing the production of higher-mass states (or states produced with more transverse momentum) than the conventional Drell-Yan processes involving virtual photons, Z's, or gluons.

B. Processes mediated by W_I exchange

Every member of one column of the $(\mathbf{2}_I, \mathbf{6}^*)_L$ multiplet in Eq. (1) can couple to the corresponding member of the other column through emission or absorption of a (probably virtual) W_I. In some cases, as in top quark decay, the gauge boson which mediates the decay may even be on its mass shell. There thus arises the possibility of a new class of β decays, whose details depend on the combined masses of various doublets of $SU(2)_I$.

We have argued that the states n are likely to be fairly light. One possibility for the end product of decays mediated by W_I exchange is for them to involve $N\bar{n}$ pairs. This mechanism will make sense if $\bar{N}$ does not acquire too large a Majorana mass, or is somehow prevented from acquiring a Dirac mass in combination with ν. A means must then be found for the $\bar{N}$ to decay. This may take place through a radiative mechanism such as $\bar{N} \to \gamma n$. Such processes can arise as a result of loop diagrams involving mixing [17,18]. The lifetime must be sufficiently short so that the decay occurs within the detector (so that photons are detected), but not short enough to imply large flavor-changing neutral currents, on which there are stringent constraints [26]. In the following subsection we discuss the appropriate constraints in more detail.

An alternative ‘‘lightest pair’’ would be $\nu_E\overline{\nu_e}$. In that case it would be the ν_E which would have to undergo radiative decay, perhaps to $\gamma\nu_e$.

Box diagrams involving W_I exchange and intermediate h-type quarks can lead to effective flavor-changing neutral interactions of the right-handed d, s, and b quarks or their left-handed antiquark counterparts [as these are the ones in $\mathrm{SU}(2)_I$ doublets]. The suppression of these interactions below the levels of ordinary flavor-changing neutral interactions induced by $\mathrm{SU}(2)_L$ interactions imposes constraints on the Cabibbo-Kobayashi-Maskawa- (CKM)-like matrix describing the $\mathrm{SU}(2)_I$ couplings between d, s, b and the corresponding h-type quarks. These appear to be easily satisfied for h-type quarks no heavier than the top quark and W_I masses in the range of several hundred GeV. A more serious constraint could, in principle, arise from the process $\mu\rightarrow e\gamma$, which can be mediated by loops involving a W_I and an intermediate exotic charged lepton. Retracing steps taken in [27], it turns out that with reasonable assumptions about mixing between light and heavy leptons this process is predicted to occur at a rate below present limits.

C. Constraints on radiative decay

We now return to the decay $\overline{N}\rightarrow\gamma n$ which must take place through a loop diagram as a result of mixing. The discussions of [17,18,27] can be adapted to evaluate the rate under any given set of assumptions. For illustration, we assume that loop diagrams involving ordinary W’s and charged leptons e^- and E^- are responsible for the decays, with the weak eigenstates coupled to the W’s and charged leptons corresponding to mixtures between ν_E and $\overline{N}_e$ and between ν_e and n_e. If $\overline{N}_e$ has mass M and n_e has mass m, the rate for $\overline{N}_e\rightarrow\gamma n_e$ is [17]

$$\Gamma\approx\frac{\alpha G_F^2M^3\overline{M^2}}{16\pi^4}\left(1-\frac{m^2}{M^2}\right)^3, \qquad (4)$$

where $\overline{M}$ represents a sum of charged lepton masses weighted by products of mixing factors, and we have used the crude approximation $M\ll M_W$. For $m\ll M=50$ GeV (an illustrative mass) and $\overline{M}=50$ GeV (as one might expect if the mixing factors were of order unity), one obtains a decay rate of order 3×10^{17} s^{-1}. If $\overline{M}$ is a factor of 10^4 smaller (corresponding to reduction of each mixing factor by 10^2), the decay rate is still 3×10^9 s^{-1}, comfortably within the detector. (Note that the secondary vertex for $\overline{N}_e\rightarrow\gamma n_e$ will not be visible; all that is required is that the decay occurs before the electromagnetic calorimeter.) A mixing factor for the ν_e below 10^{-2} will be consistent with weak universality, and no problems with flavor-changing neutral currents are anticipated as long as such mixings are confined to the neutral lepton sector.

D. Interpretation of the CDF $e^+e^-\gamma\gamma\not{E}_T$ event

One event of the form $p\bar{p}\rightarrow e^+e^-\gamma\gamma\not{E}_T+\cdots$ (event 257 646 of run 68 739) has been reported at $\sqrt{s}=1.8$ TeV by the CDF Collaboration at the Fermilab Tevatron [8]. A possible interpretation of this event is the production of an E^-E^+ pair via the subprocess $d\bar{d}\rightarrow Z_I\rightarrow E^-E^+$ (which has a maximal negative forward-backward asymmetry $A_{\mathrm{FB}}=-3/4$, as does $d\bar{d}\rightarrow Z_I\rightarrow e^-e^+$). The $E^\pm$ states then decay to $e^\pm$ and virtual (or perhaps real) W_I’s, which then materialize into whatever doublets of $\mathrm{SU}(2)_I$ are energetically accessible (such as the possibilities mentioned above). The decays of virtual W_I’s are thus conceivable sources of photons + (missing energy) in a wide class of events.

A likely mass for E lies between the maximum beam energy currently attained by LEP (80.5 GeV) and slightly below one-half the mass of the Z_I candidate mentioned above (511 GeV/2≃250 GeV). Depending on the masses of the other exotic fermions, the Z_I could decay to a number of pairs of such states, including exotic charged leptons which we may call M and T of the second and third families, $h\bar{h}$ (for one or more families) and the $\mathrm{SU}(2)_I$-doublet exotic neutral leptons [see Eq. (1)]. At the very least, one should expect to see at least one $\nu_E\overline{\nu_E}$ pair, most likely leading to a pair of photons and missing energy as discussed below in Sec. IV A.

E. Scalar particles

The existence of an extended Higgs structure within E_6, based on bosons belonging to the **27**-plet, implies that, in addition to the neutral bosons noted in Table I, there are likely to be some light scalars with electromagnetic charges $Q=\pm1$. (Some of the corresponding colored scalars can mediate proton decay and must be very heavy [28].) We mention this possibility only to note how rich the E_6 spectrum is likely to be; to demonstrate that it is evidence for supersymmetry may require considerable effort, such as the comparison of couplings with one another.

F. Other signatures in hadron collisions

The exchange of virtual W_I quanta can lead to the production of pairs of exotic quarks through the process $d\bar{d}\rightarrow h\bar{h}$ at subenergies below that where direct Z_I production can contribute [7]. Whether through W_I exchange or via Z_I in the direct channel, the angular asymmetry of the subprocess should be maximal (i.e., $A_{\mathrm{FB}}=3/4$) in the forward direction. The decays of h and $\bar{h}$ will be similar to those of E^+ and E^-, but with down-type quarks replacing charged leptons.

Production of $\nu_E\overline{\nu_E}$ pairs through Z_I decay should lead to pairs of photons + (missing energy) if the major decay modes of ν_E are radiative or involve a radiative chain.

It may be that decays such as $E^-\rightarrow\nu_E+(\cdots)^-$ can compete favorably with decays mediated by W_I. In that case the system $(\cdots)$ can be any decay product of a (probably virtual) W^-, and may include hadron jets as well as leptons of any flavor. However, if a large weak-isosinglet Dirac mass is induced for both E and ν_E, these two states may be fairly close to each other in mass.

G. CDF trilepton event

Another exotic event (run 67 581/event 129 896) reported by the CDF Collaboration [8] involves an e^+e^- pair, a

TABLE II. Cross sections σ [in units of $\sigma_0 \equiv \sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)$] for e^+e^- production of pairs of fermions $f\bar{f}$ via virtual photons and Z's in the direct channel. Here, t-channel exchanges are neglected for e and ν_e. The ν_E is assumed to be a Dirac neutrino. Values of g_V^f are quoted for $x=0.2315$. QCD corrections to quark production have been neglected.

Fermion f	Q_f	g_V^f	g_A^f	σ/σ_0 far below Z	σ/σ_0 far above Z
u	2/3	0.0957	−1/4	4/3	1.80
d	−1/3	−0.1728	1/4	1/3	0.92
e^-	−1	−0.0185	1/4	1	1.13
ν_e	0	1/4	−1/4	0	0.25
h	−1/3	0.0772	0	1/3	0.35
E^-	−1	−0.2685	0	1	1.20
ν_E	0	1/2	0	0	0.50

μ^-, a jet, and missing transverse energy. This could be due to $Z_I \to E^+E^-$, where the decays of $E^\pm$ lead to subsequent $e^\pm$ pairs, possibly through chains of ordinary weak charge-changing transitions. The muon and missing energy might be the decay products of one such (perhaps virtual) W, while the jet might be the (merged) decay products of another.

IV. OTHER COLLIDERS

A. Electron-positron colliders

The reaction $e^+e^- \to Z_I \to \cdots$ is an obvious gateway to new physics. However [7], one can also expect an observable rate for W_I exchange in the process $e^+e^- \to E^+E^-$ even at energies not corresponding to Z_I formation in the direct channel. Moreover, all the exotic fermions with the exception of N_e and n_e can be produced via virtual photons and/or Z's in the direct channel.

Define $x \equiv \sin^2\theta$, $s \equiv E^2_{\text{c.m.}}$, and $r \equiv [s/(s-m_Z^2)x(1-x)]$. Then, far from the Z pole, where the Z width can be neglected, the contribution of a virtual photon and Z in the direct channel to the cross section for production of a fermion, with electric charge Q_f and axial and vector Z couplings g_A and g_V, is

$$\sigma(e^+e^- \to f\bar{f}) = \sigma_\gamma \left\{ Q_f^2 - 2rQ_f g_V^e g_V^f + r^2[(g_V^e)^2 + (g_A^e)^2] \times \left[(g_V^f)^2 + \frac{\beta^2}{K_V}(g_A^f)^2 \right] \right\}, \tag{5}$$

where

$$\sigma_\gamma \equiv \frac{4\pi\alpha^2}{3s} N_c \beta K_V, \quad \beta \equiv \left(1 - \frac{4m_f^2}{s}\right)^{1/2}, \quad K_V \equiv \frac{3-\beta^2}{2}, \tag{6}$$

and N_c is the number of colors of fermions. For quarks $(N_c=3)$ the cross section should be multiplied by an additional correction factor of $1+(\alpha_s/\pi) \approx 1.04$. The values of σ/σ_0 far above pair production threshold, where $\sigma_0 \equiv \sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)$, are compared in Table II for various fermion species f when the energy is far below the Z pole (where only the virtual photon dominates) and when it is far above the Z (where the interference in vector contributions of the photon and Z is possible). In computing the values of g_V and g_A for E^- and a Dirac neutrino ν_E, one must recall that both left-handed and right-handed states have the same value of I_{3L}: $-1/2$ for E^- and $+1/2$ for ν_E.

All the exotic fermions h, E, and ν_E (assuming the last is a Dirac particle) are produced exclusively via their vector couplings, and so are excited with a cross section which attains its maximum not far above the threshold energy E_{th}. The peak occurs at the maximum value of $\beta(3-\beta^2)(1-\beta^2)$, or $E_{\text{c.m.}} = 1.18E_{\text{th}}$ for very heavy fermions, but somewhat lower when the ratio $M_Z/2m_f$ is nonnegligible as a result of the proximity of the Z pole. Thus, for example, for Dirac neutrinos with $m(\nu_E) = 70$, 80, 90 GeV the respective cross sections for $e^+e^- \to \nu_E\overline{\nu_E}$ peak at 2.9, 1.8, and 1.2 pb for $E_{\text{c.m.}} = 154$, 179, and 204 GeV, which are 1.10, 1.12, and 1.13 times E_{th}.

With our present interpretation of the CDF $e^+e^-\gamma\gamma\not{E}_T$ event, the lowest-energy signature for new physics in an electron-positron collider (such as LEP) could be the process $e^+e^- \to Z^* \to \nu_E\overline{\nu_E}$, followed by the radiative decay of each ν_E to γn_e. In this case, one would see events with two noncoplanar photons whose energies would become more and more monochromatic as the machine energy was lowered toward $\nu_E\overline{\nu_E}$ threshold. Such a signature is also a feature of neutralino pair production in several supersymmetric scenarios [9]. On the other hand, if it is the N_e and not the ν_E which is undergoing radiative decay, the reaction $e^+e^- \to \nu_E\overline{\nu_E}$ may still act as a gateway to the production of pairs of acoplanar photons, but their energies will not be monochromatic even at $\nu_E\overline{\nu_E}$ threshold since they will then be produced via the chain

$$\nu_E \to \nu_e W_I^* \to \nu_e N_e \overline{n_e} \to \nu_e n_e \gamma \overline{n_e}. \tag{7}$$

B. Electron-proton collisions

In electron-proton collisions, the subprocess $e^-d \to E^-h$ is allowed by W_I exchange [7]. The subprocess $e^+d \to E^+h$ involves a mismatch of $\mathrm{SU}(2)_I$ quantum numbers and is forbidden. Thus, at the DESY ep collider HERA, e^-p collisions afford a better chance than e^+p collisions for discovering the new fermions proposed here. As in other experiments, one signature for new physics would be the observation of events with isolated photons and missing transverse energy.

V. CONCLUSIONS

We have investigated some features of the symmetry chain $\mathrm{E}_6 \to \mathrm{SU}(2)_I \times \mathrm{SU}(6)$ which illustrate the richness of the group E_6 for exhibiting new physics at present-day colliders. An ''inert'' SU(2) subgroup, involving one Z_I and two W_I bosons, can manifest itself through direct production of the Z_I, production of exotic fermions, and decays of these fermions which can proceed through several chains before ending up in a radiative cascade. The present scenario is thus one which lends itself to interpretation of an event involving an $e^+e^-\gamma\gamma\not{E}_T$ final state reported by the CDF Collaboration at Fermilab. The favored interpretation is

$$\overline{pp}\to Z_I+\cdots\to E^+E^-+\cdots, \tag{8}$$

followed by the chain

$$E^-\to e^-W_I^{(*)}\to e^-\overline{N_e}\overline{n_e}\to e^-\gamma n_e\overline{n_e}, \tag{9}$$

and its charge-conjguate for E^+ decay. The n_e state is allowed to be stable as long as its mass satisfies cosmological bounds (typically less than a few tens of eV). The Z_I is a neutral gauge boson with mass greater than present limits [22] of a few hundred GeV. The W_I is probably virtual, as indicated by the asterisk in parentheses. The neutral nature of all three bosons in $SU(2)_I$ is a key feature permitting the flavor of E^- to be passed on to the electron.

Implications of the present E_6 scheme include: (1) the expectation of $\gamma\gamma$ events with missing energy but no charged lepton pairs, both in proton-antiproton collisions at $E_{\text{c.m.}}=1.8$ TeV and in electron-positron annihilations at sufficiently high energy, (2) the confirmation of other decay modes of the ‘‘gateway’’ state Z_I, and (3) the possibility of W_I-exchange processes in a number of reactions such as electron-proton collisions, leading to pair production of exotic states.

The purpose of this exercise was in part to see if the CDF event could be viewed in a manner other than that involving supersymmetry [9] (see also [10]). This being said, the present story has several features in common with the supersymmetric versions. One may, in fact, have to work rather hard to demonstrate whether the phenomena described above are really an alternative to supersymmetry, or evidence for it.

(a) The grand-unified group is SU(5). One cannot invoke multiscale symmetry breaking to obtain satisfactory predictions for the weak mixing angle or proton decay. The matter spectrum associated with supersymmetry provides a satisfactory description within SU(5), but it remains to be seen whether the spectrum of fermions and Higgs representations proposed here (which may be only part of a supersymmetric spectrum) can do as well.

(b) The exotic leptons look somewhat like charginos (or selectrons) and neutralinos, which also can decay via chains involving missing energy and photons. The missing transverse energy in the event (around 53 GeV), when compared to the average transverse energy of the observed photons and leptons (around 41 GeV), is more characteristic of a pair of missing particles as in the supersymmetry scenario than of the two $n_e\overline{n_e}$ pairs implied by the present scheme. (We are using a statistical estimate whereby 53/41 is closer to $\sqrt{2}$ than to $\sqrt{4}$.)

(c) The use of **27**-plet multiplets of E_6 both for matter (fermions) and Higgs particles (bosons) is an invitation to make the theory supersymmetric. On the other hand, we have not made the gauge sector supersymmetric; we have not necessarily invoked selection rules such as R parity which distinguish superpartners from ordinary particles; and we have not required the existence of three **27**-plets of Higgs bosons as superpartners for our three **27**-plets of fermions. Moreover, if there are light scalars corresponding to h and h, one runs the risk of a too rapid proton decay [28]. Altogether, the resemblance of the present model to supersymmetry may turn out to be somewhat superficial.

The pattern of quarks and leptons has been quite regular up to now, just as if the periodic table of the elements consisted only of rows of equal length and were missing hydrogen, helium, the transition metals, the lanthanides, and the actinides. The new heavy states proposed here are the particle analogues of the transition metals. The light ones could be the analogues of hydrogen and helium. Such new states could help us to make sense of the pattern of the masses of the more familiar ones.

ACKNOWLEDGMENTS

I thank the CERN Theory Group for hospitality during this study, and G. Alexander, P. Frampton, H. Frisch, D. London, M. Mangano, M. Schmitt, S. C. C. Ting, and M. Veltman for fruitful discussions. This work was supported in part by the United States Department of Energy under Contract No. DE FG02 90ER40560.

---

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

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

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

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

[5] For a review of E_6 phenomenology in the context of superstring theories, see J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989). Other discussions of extended gauge structures motivated by E_6 include those by L. S. Durkin and P. Langacker, Phys. Lett. **166B**, 436 (1986); U. Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987); F. del Aguila, M. Quíros, and F. Zwirner, Nucl. Phys. **B287**, 457 (1987); P. Langacker and M. Luo, Phys. Rev. D **45**, 278 (1992); 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. Cvetič and P. Langacker, Phys. Rev. D **54**, 3570 (1996).

[6] R. W. Robinett and J. L. Rosner, Phys. Rev. D **26**, 2396 (1982).

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

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

[9] S. Ambrosanio, G. L. Kane, G. D. Kribs, S. P. Martin, and S. Mrenna, Phys. Rev. Lett. **76**, 3498 (1996); Phys. Rev. D **54**, 5395 (1996); **55**, 1372 (1997); S. Dimopoulos, M. Dine, S. Raby, and S. Thomas, Phys. Rev. Lett. **76**, 3494 (1996); S. Dimopoulos, S. Thomas, and J. D. Wells, Phys. Rev. D **54**, 3283 (1996); Stanford Linear Accelerator Center Report No. SLAC-PUB-7237, hep-ph/9609434 (unpublished); S. Dimopoulos, M. Dine, S. Raby, S. Thomas, and J. D. Wells, Report No. SLAC-PUB-7236, hep-ph/9607450 (unpublished); J. L. Lopez and D. V. Nanopoulos, Mod. Phys. Lett A **10,** 2473 (1996); Report No. DOE/ER/40717-32 [hep-ph/9608275] (unpublished); K. S. Babu, C. Kolda, and F. Wilczek, Phys. Rev. Lett. **77**, 3070 (1996); J. Hisano, K. Tobe, and T. Yanagida, Phys. Rev. D **55**, 411 (1997).

[10] G. Bhattacharyya and R. N. Mohapatra, Phys. Rev. D **54**, 4204 (1996).

[11] E. Witten, Nucl. Phys. **B268**, 79 (1986).

[12] E. Ma, Phys. Lett. B **380**, 286 (1996).

[13] J. L. Rosner, Phys. Lett. B **387**, 113 (1996).

[14] Rosner [4].

[15] S. Nandi and U. Sarkar, Phys. Rev. Lett. **56**, 564 (1986).

[16] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, Proceedings of the Workshop, Stony Brook, New York, 1979, edited by P. van Nieuwenhuizen and D. Z. Freedman (North-Holland, Amsterdam, 1979), p. 315; T. Yanagida, in *Proceedings of the Workshop on Unified Theory and Baryon Number in the Universe*, Tsukuba, Japan, 1979, edited by O. Sawada and A. Sugamoto (KEK Report No. 79-18, Tsukuba, Japan, 1979).

[17] T. Rizzo, Phys. Rev. D **36**, 303 (1987).

[18] K. Enqvist and J. Maalampi, Phys. Lett. B **180**, 347 (1986).

[19] See, e.g., E. Ma, Mod. Phys. Lett. **11**, 1893 (1996); Hewett and Rizzo [5], and earlier references therein.

[20] D. Chang and R. N. Mohapatra, Phys. Lett. B **175**, 304 (1986).

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

[22] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **51**, 949 (1995); T. Kamon, Fermilab Report No. FERMILAB-CONF-96-106-E, hep-ex/9605006, presented at XXXI Rencontre de Moriond: QCD and High-energy Hadronic Interactions, 1996 (unpublished); CDF Collaboration, M. K. Pillai, E. Hayashi, K. Maeshima, C. Grosso-Pilcher, P. de Barbaro, A. Bodek, B. Kim, and W. Sakumoto, Report No. hep-ex/9608006, presented at Division of Particles and Fields Meeting, American Physical Society, Minneapolis, MN, 1996 (unpublished).

[23] J. F. Gunion *et al.*, Int. J. Mod. Phys. A **2**, 1199 (1987); S. Nandi, Phys. Lett. B **197**, 144 (1987); Hewett and Rizzo [5].

[24] J. L. Rosner, Phys. Rev. D **54**, 1078 (1996).

[25] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **77**, 2616 (1996).

[26] Hewett and Rizzo [5]; M. Gronau and D. London, this issue, Phys. Rev. D **55**, 2845 (1997).

[27] G. Jungman and J. L. Rosner, Phys. Lett. B **277**, 177 (1992).

[28] S. Dimopoulos and H. Georgi, Nucl. Phys. **B193**, 150 (1981).