Exotic fermions

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Exotic fermions, i.e., fermions with quantum numbers in the standard group $[SU(3)_C \times SU(2)_L \times U(1)_Y]$ different from those of quarks and leptons and/or spin $\frac{3}{2}$, are possible candidates for new particles likely to be observed at or above 100 GeV. Two phenomenological lists of exotic fermions are produced, one based on the interaction of the hypothesized exotics with ordinary quarks and leptons via gauge bosons associated with the standard group and the other arising from gauge bosons associated with the enlarged group $[SU(4)_C \times SU(2)_L \times SU(2)_R]$ which contains $B-L$ as a generator. An independent list of exotic fermions in the form of three-preon composites, possessing relatively low masses and special modes of decay, is predicted by the chiral $E_6 \otimes SO(10)$ preon model. The connection between the phenomenological and preon-generated exotic fermions is discussed, as is the experimental signatures of these exotics.

I. INTRODUCTION

The new phenomena observed on the $p\bar{p}$ collider (e.g., anomalous decays of the Z boson into leptons and a photon, monojet events, etc.)[1] have greatly accelerated interest in deviations from the standard model and in the existence of new particles at or above the 100-GeV region. This interest is obviously enhanced by the prospect that even-higher-energy accelerators will become operative in the not-too-distant future. Unfortunately, as of now, the data from the $p\bar{p}$ collider are very meager and so it is not surprising that every explanation of the anomalous events—whether it be composite structure of the weak bosons, new scalar particles, or excited leptons, among others[2]—has been found wanting.[3] In view of this situation, we wish to bring together in this paper some arguments for the possible existence and experimental signatures of a class of particles, which we call "exotic fermions,"[4] that could be responsible for new phenomena at or above 100 GeV. The term "exotic fermions" includes fermionic states with color-flavor quantum numbers (QN's) in the standard group $SU(3)_C \times SU(2)_L \times U(1)_Y$ different from the QN's of quarks and leptons ("internally" excited states of quark and leptons) as well as fermionic states with spin $\frac{3}{2}$ ("spin" excited states of quarks or leptons)[5] or a combination of both ("spin" and "internally" states of quarks and leptons). It should be emphasized that the exotic fermions about which we speak have nothing to do with the gauginos, Higgs fermions, and gravitinos of supersymmetry and supergravity.

We approach the question of identifying possible candidates for exotic fermions in two ways. In the first approach, discussed in Sec. II, we adopt the phenomenological or model-independent approach and consider exotic fermions that can arise from interaction with the ordinary quarks and leptons via gauge bosons. The gauge bosons are assumed to belong to either $SU(3)_C \times SU(2)_L \times U(1)_Y$ [the maximal subgroup of SU(5)] or to $SU(4)_C \times SU(2)_L \times SU(2)_R$ [the only viable maximal subgroup of SO(10) (Ref. 6)].

In the second approach, discussed in Sec. III, we take the lead from the composite theory of quarks and leptons and present a list of possible candidates for exotic fermions predicted by a chiral three-preon model that we find particularly attractive. This chiral $E_6 \otimes SO(10)$ model[7] produces a set of exotics that overlaps in a surprising fashion with the set of exotics deduced in one of the phenomenological approaches. Finally, in Sec. IV, we make some concluding comments.

II. PHENOMENOLOGY OF EXOTIC FERMIONS

Let us be more precise about our definition of exotic fermions. As stated, we mean fermions with QN's in $SU(3)_C \times SU(2)_L \times U(1)_Y$ different from those of quarks and leptons. The QN's of quarks and leptons are $(3,2)_{1/6}$, $(\bar{3},1)_{1/3,-2/3}$, $(1,2)_{-1/2}$, $(1,1)_{1,0}$ of $(SU(3)_C, SU(2)_L)_Y$ where we have used the Weyl fermion notation and $Q=I_{3L}+Y$. With exotic fermions thus defined, let us consider the possibility of producing them by gauge bosons, i.e., gluons, W's, Z's, or photons. The most obvious mechanism is pair production by a gauge boson. In this case, one can evidently create almost any exotic fermion since $r \times \bar{r}$ (r is the representation of an exotic fermion) always contains singlet and adjoint representations and the gauge boson belongs to the adjoint representation. Thus, e.g., if an exotic fermion has color charge, then it can be produced pairwise by a gluon. However, since we expect these exotic fermions to be heavy, this process is restricted by the kinematics. The operator responsible for this process is dimension (dim) 4 for spin $\frac{1}{2}$ and $\frac{3}{2}$.

Next, let us consider associated production of an exotic fermion together with an ordinary fermion (quark or lepton) by gauge bosons. If an ordinary fermion is a composite object, then it is very likely to have this interaction. If this interaction is present, one can also use it in the deep-inelastic scattering process to produce exotics. If the (metacolor) binding force scale is much larger than the W and Z masses, we expect that this interaction will respect the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry. Then, because of gauge invariance, this interaction starts from dim-5 operators.[8] Therefore, it is suppressed at least by M^{-1} where M is some mass scale. In this case, the QN's of the exotic fermions are restricted by the QN's of the ordinary fermions as shown in Table I. A gluon can produce the following exotics in association with quarks: $(\overline{6},2)_{1/6}$, $(6,1)_{1/3,-2/3}$, $(15,2)_{1/6}$, $(\overline{15},1)_{1/3,-2/3}$; and in association with leptons: $(8,2)_{-1/2}$ and $(8,1)_{1,0}$. The production cross section should be of the order of the strong-interaction cross section suppressed by the factor M^{-2}. A W or Z boson or a photon can produce the exotics $(3,4)_{1/6}$, $(\overline{3},3)_{1/3,-2/3}$, $(1,4)_{-1/2}$, and $(1,3)_{1,0}$. The rate must be below the W and Z rate.

The helicity structures depend upon the operators responsible for the interaction. The dim-5 operator for spin $\frac{1}{2}$ has the structure[9]

$$\frac{1}{M} F_{\mu\nu} \overline{E}_R \sigma^{\mu\nu} \psi_L + (L \leftrightarrow R) , \tag{1}$$

where $E(\psi)$ denotes the exotic (ordinary) fermion and $F_{\mu\nu}$ the gauge boson. The dim-5 operator for spin $\frac{3}{2}$ has the structure[4]

$$\frac{1}{M} F_{\mu\nu} \overline{G}_L^{\mu\nu} \psi_L + (L \leftrightarrow R) , \tag{2}$$

where

$$G_{\alpha\beta} = \gamma_\alpha E_\beta - \gamma_\beta E_\alpha . \tag{2a}$$

Note that for spin $\frac{1}{2}$ the operator is *not chiral invariant,* while for spin $\frac{3}{2}$ it is. Thus, if the theory possesses exact chiral symmetry, the dim-5 operator for spin $\frac{1}{2}$ is forbidden.

The dim-6 operator for spin $\frac{1}{2}$ is[9]

$$\frac{1}{M^2} F_{\mu\nu} \overline{E}_L \gamma^{[\mu} \partial^{\nu]} \psi_L + (L \leftrightarrow R) \tag{3}$$

while for spin $\frac{3}{2}$ it can be, among many possibilities,

$$\frac{1}{M^2} F_{\mu\nu} \overline{H}_R^{\mu\nu} \psi_L + (L \leftrightarrow R) , \tag{4}$$

where

$$H_{\alpha\beta} = \partial_\alpha E_\beta - \partial_\beta E_\alpha . \tag{4a}$$

Thus, for spin $\frac{1}{2}$ the dim-6 operator is chiral invariant, while for spin $\frac{3}{2}$ it is not. Therefore, the production of spin-$\frac{3}{2}$ exotics is less suppressed than spin-$\frac{1}{2}$ exotics, by M^{-2}, if chiral symmetry is respected.

What are the experimental signatures of these exotic fermions? We can use the interaction above in the opposite direction. An exotic fermion, produced with a quark from a gluon or with a gluon from a quark, has a higher-dimensional representation in color, and thus it can emit many gluons and finally decays into an ordinary quark and gluon. Consequently, if it exists, we should see an increase in multiplicity and two hard jets (one from a quark and the other from a gluon), as we start producing it. [If the measure of the gluon multiplicity is proportional to the second-order Casimir invariant of SU(3), then $\overline{\mathbf{6}}$ gives 2.5 times, **8** 2.25 times, and **15** 4 times more, compared with a quark **3**, since $I_2(\mathbf{3}) = \frac{4}{3}$, $I_2(\overline{\mathbf{6}}) = \frac{10}{3}$, $I_2(\mathbf{8}) = 3$, and $I_2(\mathbf{15}) = \frac{16}{3}$.] The exotic fermion associated with a lepton is a strange object; it is a color octet but its electric charge is an integer: 0 or ± 1. Again, it can emit many gluons and finally decay into a lepton and a gluon. Thus, we would see a high-p_T lepton and a jet. If this exotic fermion is neutral, then we have the large missing transverse energy,[9] which looks like a monojet event, although the jet produced in this process is a gluon jet and thus broader than that produced by a quark. For weak exotics, i.e., $(3,4)_{1/6}$, $(1,4)_{-1/2}$, $(\overline{3},3)_{1/3,-2/3}$, or $(1,3)_{1,0}$ exotics, they must decay into a W (or a Z or a photon) and an ordinary fermion. Thus, the invariant mass of a W and a lepton, a Z and a lepton, or a hard photon and a lepton may reveal the existence of $(1,3)_{1,0}$. (Compared with the first possibility, the second one is suppressed at least by $\cos^2\theta_W$ while the third one is suppressed at least by $\sin^2\theta_W$.) In order to give these weak exotics a mass, one needs at least one Higgs triplet and then the Higgs spectrum will be rich. As can be seen from Table I, if the standard group $SU(3)_C \times SU(2)_L \times U(1)_Y$ is applicable, one would expect the decays of the exotic fermions into W and Z bosons to behave in a similar fashion unless an exotic lies between the masses of W and Z.

In addition to "internally" excited fermions, one can expect excited fermions which have the same quantum numbers as quarks and leptons. According to the experience in QCD hadron physics, the lowest massive ones would be $J = \frac{3}{2}$ states (rather than radially excited ones), if quarks and leptons are composed of three fermions. However, if they are heavy, they can emit many scalar particles consisting of two preons and thus they would be hard to identify. The exception is for chiral preon models, which do not have scalar two-preon bound states (see Sec. III). In that case, the dominant decay mode could be an ordinary fermion plus a gluon or a photon. Consequently, we can expect to have both $Z \to l\bar{l}\gamma$ and $W \to l\gamma\bar{\nu}$. Note that the $J = \frac{3}{2}$ state is preferred over the $J = \frac{1}{2}$ state, since the

TABLE I. $(SU(3)_C, SU(2)_L)_Y$ quantum numbers of exotic fermions in interaction with gauge bosons of $SU(3)_C \times SU(2)_L \times U(1)_Y$ group (first row gives QN's of ordinary fermions).

	$(3,2)_{1/6}$	$(\overline{3},1)_{1/3,-2/3}$	$(1,2)_{-1/2}$	$(1,1)_{1,0}$
Gluon $(8,1)_0$	$(3,2)_{1/6}$ $(\overline{6},2)_{1/6}$ $(15,2)_{1/6}$	$(\overline{3},1)_{1/3,-2/3}$ $(6,1)_{1/3,-2/3}$ $(\overline{15},1)_{1/3,-2/3}$	$(8,2)_{-1/2}$	$(8,1)_{1,0}$
$SU(2)_L$ $(1,3)_0$	$(3,2)_{1/6}$ $(3,4)_{1/6}$	$(\overline{3},3)_{1/3,-2/3}$	$(1,2)_{-1/2}$ $(1,4)_{-1/2}$	$(1,3)_{1,0}$
$U(1)_Y$ $(1,1)_0$	$(3,2)_{1/6}$	$(\overline{3},1)_{1/3,-2/3}$	$(1,2)_{-1/2}$	$(1,1)_{1,0}$

dim-5 operator for $J=\frac{1}{2}$ is not chiral invariant. Another reason for preferring $J=\frac{3}{2}$ is that if the dim-5 operator is responsible for $J=\frac{1}{2}$ exotic particle decay into a photon and an ordinary lepton, then this $J=\frac{1}{2}$ state can be neither a left-handed doublet nor a right-handed singlet, since $\overline{E}_L\sigma^{\mu\nu}\psi_R$ behaves as a doublet (not as a triplet) if E_L is a doublet in $SU(2)_L$ and vice versa, as emphasized by Suzuki.[10] Further constraints come from the anomalous magnetic moment for leptons[11] and the flavor-changing neutral current.[12]

Is it possible to find new phenomena only in Z decays, but not in W decays? This possibility has been discussed within the framework of composite W and Z's (Ref. 13). Here, we suggest another explanation for this possibility, by enlarging the group structure of the color-flavor symmetry. That is, a distinction can arise between W and Z decays, if the color-flavor gauge group is larger than $SU(3)_C\times SU(2)_L\times U(1)_Y$, i.e., its rank is greater than four. [Thus, in rank-4 SU(5) grand unified theory, we do not expect this to happen.] The reason is that the Z boson is a mixture of electrically neutral gauge bosons. If an exotic fermion has the QN's in the new gauge group and this gauge group contains a neutral boson, then Z will have this exotic fermion in its decay. Thus, if we find a new phenomenon in Z decay, but not in W decay, it may be indicative of the fact that the color-flavor gauge group is larger than the standard group. Hence, it is interesting to investigate this scenario in more detail, although the use of "excited leptons" with spin $\frac{1}{2}$ to explain the small number of anomalous Z decays observed[1] at CERN fails the Dalitz plot test at this stage if the "excited" lepton is "on-shell," or it does not hold up because of the unnaturally large size of the coupling constant required if it is "off-shell." Nevertheless, this effect may show up for a second Z boson in the larger group.

Let us discuss the above scenario. What does the enlarged color-flavor symmetry have to be? Obviously, enlarging $SU(2)_L$ does not work. Just making $U(1)_Y$ into many U(1)'s does not work either, since Z is neutral for those U(1)'s. [Note that $SU(2)_R$ is irrelevant in this discussion and can be replaced by $U(1)_R$.] Thus, the proper way is to enlarge the $SU(3)_C$ group and this new group must contain a new electrically neutral boson. The smallest increase in rank which works is SU(4) (rank 3). The new neutral boson is easily identified as the $U(1)_{B-L}$ boson.[14] Thus, let us use $SU(4)_C\times SU(2)_L\times SU(2)_R$ (its rank is 5, which is one higher than the standard model). The group $SU(4)_C$ contains both $SU(3)_C$ and $U(1)_{B-L}$. The electric charge is given by

$$Q=I_{3L}+I_{3R}+\tfrac{1}{2}(B-L)\ .$$

Possible exotic fermions, which can couple with the gauge bosons of the enlarged group and an ordinary fermion, are listed in Table II. Note that in this group, ordinary fermions belong to (4,2,1) plus $(\overline{4},1,2)$ of $(SU(4)_C, SU(2)_L, SU(2)_R)$.

If we decompose the exotic fermions of Table II in terms of the standard QN's, i.e., $(SU(3)_C,SU(2)_L)_Y$ $(Q=I_{3L}+Y)$, then

$$\begin{aligned}(36,2,1)&\to(6,2)_{5/6}+(15,2)_{1/6}+(8,2)_{-1/2}\\&\quad+(\overline{3},2)_{-7/6}+(3,2)_{1/6}+(1,2)_{-1/2}\ ,\\(\overline{20},2,1)&\to(8,2)_{-1/2}+(\overline{3},2)_{5/6}+(3,2)_{1/6}+(\overline{6},2)_{1/6}\ ,\\(\overline{4},3,2)&\to(\overline{3},3)_{1/3,-2/3}+(1,3)_{1,0}\ ,\\(4,4,1)&\to(3,4)_{1/6}+(1,4)_{-1/2}\ .\end{aligned}\tag{5}$$

Note that all exotics in Table I have their natural place in $SU(4)_C\times SU(2)_L\times SU(2)_R$. One should note that (36,2,1) contains new quasiquarks and quasileptons, $(3,2)_{1/6}$ and $(1,2)_{-1/2}$ of $[SU(3)_C,SU(2)_L]_Y$, while $(\overline{20},2,1)$ contains only the quasiquarks, $(3,2)_{1/6}$. These quasistates can couple to Z if such an interaction exists. We have not only $Z\to l\bar{l}\gamma$ but also $Z\to q\bar{q}\gamma$ from **36** of $SU(4)_C$, while from $\overline{\mathbf{20}}$, we have only $Z\to q\bar{q}\gamma$. However, these quasiquarks and quasileptons cannot couple to the $SU(2)_L$ bosons associated with ordinary fermions, because of their $SU(4)_C$ quantum numbers. Thus, they cannot be seen in W decays and charged-current reactions are not altered, except possibly by $SU(2)_R$ bosons. Since Z can couple to these quasiquarks, more hadronic activity in Z processes is expected. Only neutral-current reactions can provide some information on these quasiquarks and leptons, but no charged-current reactions can do so.

We substantiate the above statements by writing down the explicit group structure of the interactions. The coupling of **36** (exotic fermion) with **15** [$SU(4)_C$ gauge boson] and **4** (ordinary fermion) is $A_b^aE_a^{\{b,c\}}\psi_c$ where $A_b^a=\mathbf{15}$, $E_a^{\{b,c\}}=\mathbf{36}$, $\psi_c=\overline{\mathbf{4}}$ and they satisfy $\sum A_a^a=0$, $E_a^{\{b,c\}}=E_a^{\{c,b\}}$, and $\sum E_a^{\{a,b\}}=0$. The coupling of **20** with **15** and **4** is $A_b^aE_a^{[b,c]}\psi_c$ where $\sum E_a^{[a,b]}=0$ and $E_a^{[b,c]}=-E_a^{[c,b]}$. In order to see how the $U(1)_{B-L}$ gauge boson and gluons couple with these quasiquarks and leptons, we must decompose $SU(4)_C$ representations into $SU(3)_C\times U(1)_{B-L}$ representations. Using the appendix, we can calculate the coupling strength as follows:

$$G_\beta^\alpha 15_\alpha^{\{\beta,\gamma\}}q_\gamma+\tfrac{1}{4}G_\beta^\alpha 3^\beta q_\alpha+\tfrac{4}{3}C\,3^\gamma q_\gamma+\tfrac{4}{3}C\,1l \quad \text{from } A_b^aE_a^{\{b,c\}}\psi_c\ , \tag{6a}$$

$$G_\beta^\alpha\overline{6}_\alpha^{[\beta,\gamma]}q_\gamma-\tfrac{1}{2}G_\beta^\alpha 3^\beta q_\alpha+G_\beta^\alpha 8_\alpha^\beta l-\tfrac{1}{2}C\,3^\gamma q_\gamma \quad \text{from } A_b^aE_a^{[b,c]}\psi_c\ . \tag{6b}$$

TABLE II. $SU(4)_C\times SU(2)_L\times SU(2)_R$ quantum numbers of exotic fermions in interaction with gauge bosons of $SU(4)_C\times SU(2)_L\times SU(2)_R$ group (first row gives QN's of ordinary fermions).

	(4,2,1)	$(\overline{4},1,2)$
SU(4)	(4,2,1)	$(\overline{4},1,2)$
(15,1,1)	(36,2,1)	$(\overline{36},1,2)$
	$(\overline{20},2,1)$	(20,1,2)
$SU(2)_L$	(4,2,1)	$(\overline{4},3,2)$
(1,3,1)	(4,4,1)	
$SU(2)_R$	(4,2,3)	$(\overline{4},1,2)$
(1,1,3)		$(\overline{4},1,4)$

In Eqs. (6a) and (6b), G^α_β is the gluon, q_α is the ordinary quark, and l is the ordinary lepton ($\alpha=1,2,3$). Thus, the $U(1)_{B-L}$ boson (C), which is a component of the Z boson, actually couples with the "excited" quarks and leptons, 3^γ and 1. The relative strengths among the exotics can also be read out.

Next, we discuss the mixing angle. The most general mixing matrix with three parameters θ,ϕ,ϵ is[15]

$$\begin{bmatrix} W_L^0 \\ W_R^0 \\ Z_{B-L} \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta\cos\phi & \cos\theta\sin\phi \\ \epsilon\sin\theta & -\tan\theta\left[\epsilon\sin\theta\cos\phi+\dfrac{\sin\phi}{\sin\theta}z\right] & \tan\theta\left[-\epsilon\sin\theta\sin\phi+\dfrac{\cos\phi}{\sin\theta}z\right] \\ z & \tan\theta(\epsilon\sin\phi-z\cos\phi) & -\tan\theta(\epsilon\cos\phi+z\sin\phi) \end{bmatrix} \begin{bmatrix} A \\ Z_1 \\ Z_2 \end{bmatrix}, \tag{7}$$

where

$$z=(\cos^2\theta-\epsilon^2\sin^2\theta)^{1/2}$$

and A, Z_1, and Z_2 denote the physical photon, lighter Z, and heavier Z, respectively. The mass of the lighter Z is given by[15]

$$M_{Z_1}{}^2=\frac{M_{W_L}{}^2}{\cos^2\theta}\left[1-\frac{1}{z}\left[\epsilon\sin^2\theta+\cos^2\theta\frac{M_{12}{}^2}{M_{W_L}{}^2}\right]\tan\phi\right], \tag{8}$$

where $M_{12}{}^2$ is the (1,2) component of the mass matrix. For simplicity, let us take $\phi=0$, which leads to $M_{W_L}{}^2=M_Z{}^2\cos^2\theta$ and the second-Z-boson mass $=$infinity.[15] Then, the mixing matrix yields

$$Z_{B-L}=zA-z\tan\theta\,Z_1-\epsilon\tan\theta\,Z_2 .$$

Thus, for the matrix element, $Z_i\to\bar{\psi}E$ and $E\to\psi\gamma$ ($i=1,2$), we have $-z^2\tan\theta$ for the first (lower mass) Z and $-z\epsilon\tan\theta$ for the second (higher mass) Z. Hence, the mixing angle favors the low-mass Z to have the radiative decays, since we believe ϵ is not large.

III. EXOTIC FERMIONS IN THE $E_6\otimes SO(10)$ CHIRAL PREON MODEL

In Sec. II we have explored some phenomenological aspects of internally or spin excited states of quarks and leptons (or both), which we have called exotic fermions, with an eye to future experiments on the $p\bar{p}$ collider and the higher-energy machines under construction. The original motivation for considering the possible existence of exotic fermions with relatively low masses, say in the 100-GeV-to-10-TeV region, came from our earlier work on preon models of quarks and leptons. In our 1983 paper,[7] we pointed out that in any composite model of quarks and leptons, one expects exotic fermionic states and that these exotics could become the evidence for the composite structure of quarks and leptons even before the form factor effect is observed in quark or lepton reactions. Our more recent work on preon models (with J. M. Gipson[7]) has led to a chiral $E_6\otimes SO(10)$ model of quarks and leptons which looks so promising that we shall summarize its predictions with regard to exotic fermions.

Before doing so, we remind ourselves of the "exotic-fermion" situation in QCD. If we assume three flavors (F), the quark group is $SU(3)_C\otimes SU(3)_F$ and the application of the generalized Pauli principle leads to the well-known prediction that the lowest-mass states of the baryon spectrum are a flavor octet of $J=\frac{1}{2}$ and a flavor decouplet of $J=\frac{3}{2}$ baryons. If we decompose $SU(3)_F$ into $SU(2)_I\times U(1)_Y$, where I and Y are the "old" strong isospin and hypercharge, the nucleon acquires the QN's (2,1), and the other states of the $J=\frac{1}{2}$ octet and all members of the $J=\frac{3}{2}$ decouplet are the "exotic fermions" predicted by the quark model. Each "exotic" baryon decays rapidly into a nucleon plus a two-quark composite (i.e., pion or kaon). The question is whether there are counterparts in quark-lepton physics to the exotic-fermionic states in hadron physics. As implied above, the answer is in the affirmative if quarks and leptons are composites but clearly the details will be different because QCD is vectorlike whereas a three-preon theory of quarks and leptons must be chiral.

The $E_6\otimes SO(10)$ chiral preon model has some very desirable properties (for details, see Ref. 7): (1) It predicts exactly three generations of ordinary quarks and leptons. (2) It converts all Goldstone bosons [arising from the breaking of global SU(16) (Ref. 16) down to gauged SO(10)] into pseudo-Goldstone bosons which acquire mass on the SO(10) scale. (3) Its chiral character enables it to predict the correct gauge-hierarchy order in terms of the preonic structure of the Higgs bosons; this provides an explanation of why Λ_{MC} (Λ_{MC} is the metacolor scale) is large compared to $M_{q,l}$ in contrast to vectorlike QCD where $\Lambda_{QCD}\sim M_{baryon}$. It can also be shown that the same mechanism that keeps the masses of the ordinary quarks and leptons essentially massless on the Λ_{MC} scale, also keeps the masses of the exotic fermions of the order of or below the mass scale M_R [R is the right-handed gauge boson connected with the breaking of $SU(2)_R$], which, itself, is small compared to Λ_{MC}. (4) Another consequence of the chiral nature of the $E_6\otimes SO(10)$ model is that metacolor singlet two-preon composites are forbidden so that there should be no analogs of the pion or kaon in quark-lepton physics; this means that in contrast to QCD where exotic baryons decay primarily into ordinary baryons plus pions or kaons, the analog of this decay mode will be excluded in the decay of exotic fermions into ordinary quarks and leptons.

With these encouraging features of the $E_6\otimes SO(10)$ preon model in mind, we record the predictions of the model with respect to exotic fermions. We find that the generalization of the Pauli principle to the metacolor degree of freedom (meta-Pauli principle) leads to three irreducible $J=\frac{1}{2}$ composite fermion representations at the SO(10) level, namely, **16**, **144**, and **1200**. When these representations are decomposed in terms of the $[SU(4)_C \times SU(2)_L \times SU(2)_R]$ quantum numbers, we are able not only to identify the three generations of ordinary quarks and leptons but also a large number of exotic fermions, as follows:

$$\mathbf{16}=(4,2,1)+(\bar{4},1,2)\,, \tag{9a}$$

$$\mathbf{144}=(4,2,1)+(\bar{4},1,2)+(4,2,3)+(\bar{4},3,2)+(\overline{20},2,1)+(20,1,2)\,, \tag{9b}$$

$$\begin{aligned}\mathbf{1200}=\;&(4,2,1)+(\bar{4},1,2)+(4,2,3)+(\bar{4},3,2)+(\overline{20},2,1)+(20,1,2)+(36,2,1)+(\overline{36},1,2)\\&+(\overline{20}'',2,1)+(20'',1,2)+(\overline{20},4,1)+(20,1,4)+(\overline{20},2,3)+(20,3,2)+(36,2,3)+(\overline{36},3,2)\,.\end{aligned} \tag{9c}$$

Since each $[(4,2,1),(\bar{4},1,2)]$ pair corresponds to a single generation of ordinary quarks and leptons, it follows from Eqs. (9a)–(9c) that each SO(10) representation (**16**, **144**, or **1200**) gives rise to one generation, for a total of three. Moreover, one expects the strength of the Yukawa interaction—which is responsible for the fermion mass—to increase with the dimension of the representation. Hence we can identify the first, second, and third generations of ordinary quarks and leptons with the **16**, **144**, and **1200** representations of SO(10), respectively. Clearly, there are no exotic fermions associated with the **16** representation but there are increasingly larger numbers associated with the **144** and **1200** representations.

If we now compare the QN spectrum of exotic fermions predicted by the $E_6 \otimes SO(10)$ model [Eqs. (9b) and (9c)] with the QN spectrum listed in Table II (arrived at by simple phenomenological arguments), we note that the exotics contained in the **144** representation are all listed in Table II whereas half of those contained in the **1200** representation (the latter half) are not listed in Table II. Conversely, one set of exotics listed in Table II [the (4,4,1), $(\bar{4},1,4)$ pair] is not included among the exotics predicted by the $E_6 \otimes SO(10)$ model.

A similar situation prevails for the $J=\frac{3}{2}$ exotics. The $E_6 \otimes SO(10)$ preon model with the help of the meta-Pauli principle predicts one irreducible SO(10) representation of $J=\frac{3}{2}$ three-preon composite states, namely, **560**. The decomposition of **560** into the quantum numbers of $[SU(4)_C \times SU(2)_L \times SU(2)_R]$ leads to many of the same "internal" excitations as for $J=\frac{1}{2}$ but also to some new ones, as follows:

$$\begin{aligned}\mathbf{560}=\;&(4,2,1)+(\bar{4},1,2)+(4,2,3)+(\bar{4},3,2)\\&+(4,4,1)+(\bar{4},1,4)+(\overline{20},2,1)+(20,1,2)\\&+(\overline{20},2,3)+(20,3,2)+(36,2,1)+(\overline{36},1,2)\,.\end{aligned} \tag{10}$$

Comparison of Eq. (10) with Table II shows only one difference between the phenomenological and preon sets: the set of exotics defined by the quantum numbers (4,2,1), $(\bar{4},1,2)$ in Table II is replaced by $(\overline{20},2,3)$, (20,3,2) in Eq. (10). There is thus a close correspondence between the $J=\frac{3}{2}$ exotics deduced phenomenologically and those predicted by the $E_6 \otimes SO(10)$ preon model. The physical content of the $E_6 \otimes SO(10)$ model lies precisely in the well-defined QN spectrum of exotic fermions predicted by the model and some day, we hope, experiment will be able to test the underlying assumptions of the theory.

IV. CONCLUDING REMARKS

We have shown how phenomenological considerations can generate lists of possible candidates for exotic fermions. We have produced two such lists, one based on the interaction of the hypothesized exotic fermions with the ordinary quarks and leptons via the gauge bosons of the standard (rank 4) group $SU(3)_C \times SU(2)_L \times U(1)_Y$, and the second on the basis of the gauge bosons associated with the enlarged (rank 5) group having $B-L$ as a generator, namely, $SU(4)_C \times SU(2)_L \times SU(2)_R$. We have also discussed some possible experimental signatures of gauge-boson decays into exotic fermions plus ordinary quarks and leptons and, in turn, of exotic-fermion decays into ordinary quarks and leptons. Not surprisingly, the first list of phenomenological exotics (Table I) is less interesting than the second set (Table II). For example, new phenomena involving exotic fermions can occur in Z but not W decays for the exotics of Table II. In addition, the exotic fermions of Table II include some very interesting objects: leptonlike states with charges up to 1 and -2, colored fractionally charged states with charges up to $\frac{4}{3}$ and $-\frac{5}{3}$, quarklike states with charges up to $\frac{5}{3}$ and $-\frac{4}{3}$, and, of course, spin-$\frac{3}{2}$ states with similar quantum numbers. Some of these exotic fermions will be relatively easy to detect, such as "leptons" with electric charges of $+1$ and -2, or the decay of an excited "lepton" into an ordinary lepton and photon. The detection of most exotic fermions will, however, require indirect and painstaking experiments.

From the theoretical point of view, it is difficult to believe that the great variety of excited baryonic states in hadron physics will not have their counterparts as a rich spectrum of exotic fermions in quark-lepton physics. This is especially true if the explanation of the three generations of quarks and leptons lies in a common preonic structure. In this paper we have therefore presented a list of exotic fermionic states predicted by a preon model, $E_6 \otimes SO(10)$, that is the sole survivor of a fairly general preon-model-building procedure. The set of exotic fermions predicted by the $E_6 \otimes SO(10)$ model replicates quite closely the set of exotics listed in Table II. Such differences as do exist [e.g., the preon-generated spectrum of exotics is somewhat richer in color fractionally charged states (going up to charges as high as $\frac{7}{3}$, and $-\frac{8}{3}$) than the phenomenological spectrum based on the $SU(4)_C \times SU(2)_L \times SU(2)_R$ gauge bosons] could some day be decided by experiment if and when the appropriate thresholds are attained in the laboratory.

We also called attention to two consequences for exotic fermions of the chiral nature of the $E_6 \otimes SO(10)$ preon model; namely, (1) the masses of the composite three-preon exotic fermions can be much less than the metacolor scale (of the order of the W_L and W_R mass scales), and (2) the decays of the exotic fermions into quarks and leptons can take place without being accompanied by composite two-preon pseudoscalars (the counterparts of pions and kaons in hadron physics). These are important qualitative statements and the real challenge now is to make quantitative predictions on the basis of the $E_6 \otimes SO(10)$ preon model. This is a difficult undertaking and it is likely that experiment and theory will have to help each other.

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APPENDIX: DECOMPOSITION OF $SU(4)_C$ TENSORS IN TERMS OF $SU(3)_C$ TENSORS

In this appendix, we decompose $SU(4)_C$ tensors in terms of $SU(3)_C$ tensors. First, let us look at the $SU(4)_C$ gauge bosons. Here, we have leptoquark bosons, gluons, and the $B-L$ boson. Since we are interested only in gluons and the $B-L$ boson, the relevant tensors are only A^α_β $(\alpha,\beta=1,2,3)$ and A^4_4. We express the gluons G^α_β and the $B-L$ boson, C, in terms of $SU(4)_C$ tensors:

$$G^\alpha_\beta \equiv A^\alpha_\beta - \tfrac{1}{3}\delta^\alpha_\beta A^\gamma_\gamma\ ,\qquad C \equiv -A^4_4\ , \tag{A1}$$

where the minus sign for C is just a phase convention. (The reason for this choice will become clear soon.) Note that G^α_β is traceless. However, since A^a_b $(a,b=1,2,3,4)$ is irreducible, we have $A^a_a=0$, which, in turn, gives $A^\gamma_\gamma + A^4_4 = A^\gamma_\gamma - C = 0$. Thus, Eq. (A1) can be rewritten in terms of the $SU(3)_C \times U(1)_{B-L}$ bosons:

$$A^\alpha_\beta = G^\alpha_\beta + \tfrac{1}{3}\delta^\alpha_\beta C\ ,\qquad A^4_4 = -C\ . \tag{A2}$$

Let us confirm that C is really a $B-L$ boson and G^α_β are the gluons, by looking at the coupling of the ordinary fermions ψ_a with the $SU(4)_C$ bosons A^a_b:

$$\bar\psi^b A^a_b \psi_a \quad (a,b=1,2,3,4)\ . \tag{A3}$$

The part of Eq. (A3) that contains the gluon and $(B-L)$ boson interactions is

$$\bar\psi^\beta A^\alpha_\beta \psi_\alpha + \bar\psi^4 A^4_4 \psi_4 = \bar\psi^\beta G^\alpha_\beta \psi_\alpha + \tfrac{1}{3}\bar\psi^\alpha C \psi_\alpha - \bar\psi^4 C \psi_4 \quad (\alpha,\beta=1,2,3)\ . \tag{A4}$$

Since ψ^α is a quark and ψ^4 is a lepton, one can see easily from Eq. (A4) that C couples to quarks with the weight $\frac{1}{3}$ and to leptons with the weight (-1). The gluons couple only with quarks.

Next, look at **36** of $SU(4)_C$, $E^{\{b,c\}}_a$. We know that **36** contains $\mathbf{15}+\mathbf{8}+\mathbf{6}+\mathbf{3}+\bar{\mathbf{3}}+\mathbf{1}$ of $SU(3)_C$. The method is similar to the above: express $SU(3)_C$ tensors in terms of $SU(4)_C$ tensors and rewrite them. We discuss only 15 and the rest are easily done. The tensor **15** of $SU(3)_C$ can be expressed in terms of $SU(4)_C$ tensors as follows:

$$\mathbf{15}^{\{\beta,\gamma\}}_\alpha = E^{\{\beta,\gamma\}}_\alpha - \tfrac{1}{4}(\delta^\beta_\alpha E^{\{\epsilon,\gamma\}}_\epsilon + \delta^\gamma_\alpha E^{\{\epsilon,\beta\}}_\epsilon)\ , \tag{A5}$$

where $\alpha,\beta,\gamma,\epsilon$ take values of 1,2,3. However, $E^{\{b,c\}}_a$ is irreducible in $SU(4)_C$ and thus we have

$$0 = \sum E^{\{a,\beta\}}_a = E^{\{\alpha,\beta\}}_\alpha + E^{\{4,\beta\}}_4\ . \tag{A6}$$

The tensor $E^{\{4,\beta\}}_4$ behaves as **3** of $SU(3)_C$ and we identify it as $-\mathbf{3}^\beta$ (with the phase convention). Then, the tensor $E^{\{\beta,\gamma\}}_\alpha$ can be written entirely in terms of $SU(3)_C$ tensors:

$$E^{\{\beta,\gamma\}}_\alpha = \mathbf{15}^{\{\beta,\gamma\}}_\alpha + \tfrac{1}{4}(\delta^\beta_\alpha \mathbf{3}^\gamma + \delta^\gamma_\alpha \mathbf{3}^\beta)\ . \tag{A7}$$

The rest of the tensors can be obtained similarly and the results are as follows:

$$\begin{aligned} E^{\{\beta,4\}}_\alpha &= \mathbf{8}^\beta_\alpha + \tfrac{1}{3}\delta^\beta_\alpha \mathbf{1}\ ,\\ E^{\{\alpha,\beta\}}_4 &= \mathbf{6}^{\{\alpha,\beta\}}\ ,\\ E^{\{\alpha,4\}}_4 &= -\mathbf{3}^\alpha\ ,\\ E^{\{4,4\}}_4 &= -\mathbf{1}\ ,\\ E^{\{4,4\}}_\alpha &= \bar{\mathbf{3}}_\alpha\ . \end{aligned} \tag{A8}$$

The case of $E^{[b,c]}_a$ can be done similarly and the results are

$$\begin{aligned} E^{[\beta,\gamma]}_\alpha &= \bar{\mathbf{6}}^{[\beta,\gamma]}_\alpha + \tfrac{1}{2}\delta^\beta_\alpha \mathbf{3}^\gamma - \tfrac{1}{2}\delta^\gamma_\alpha \mathbf{3}^\beta\ ,\\ E^{[4,\beta]}_4 &= -\mathbf{3}^\beta\ ,\\ E^{[\beta,4]}_\alpha &= \mathbf{8}^\beta_\alpha\ ,\\ E^{[\alpha,\beta]}_4 &= \bar{\mathbf{3}}^{[\alpha,\beta]}\ . \end{aligned} \tag{A9}$$

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