Natural generalization of the standard model incorporating charge $\pm\frac{1}{2}$ technifermions

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An attractive hypothesis for the quantum numbers of technifermions is that they consist of a $Y=0$ weak doublet together with $Y=\pm 1$ weak singlets of opposite chirality to the doublet. Usually these particles are postulated in an *ad hoc* manner, and so there is no understanding of why technifermions do not follow the pattern of ordinary fermion representations. We show how such technifermions can arise naturally in an extension of the standard model.

An impressive amount of experimental evidence has been gathered which supports the minimal standard model (SM). For instance, experiments on neutral-current phenomena and recent precision measurements of the Z-boson mass[1] are remarkably consistent with SM expectations.

However, the extremely important symmetry-breaking sector of the theory remains almost entirely without direct experimental support. SM orthodoxy has electroweak symmetry breaking induced by nonzero vacuum expectation values (VEV's) for a fundamental spin-zero field. Although this provides an economical symmetry-breaking sector, the use of fundamental spin-zero fields in non-supersymmetric theories has been criticized on the grounds of parameter instability under renormalization (gauge hierarchy problem).

An attractive way of avoiding this difficulty is to replace the elementary spin-zero fields by a set of fermions ("technifermions"), which feel a new strong gauge interaction called "technicolor".[2] By analogy with QCD, one can easily arrange for nonzero bilinear technifermion condensates to develop, thereby breaking the electroweak symmetry dynamically. The SM gauge-boson-mass relations remain unchanged in this scenario, and thus it is still phenomenologically viable.

There are two standard assignments for technifermions under the SM gauge group $G_{\rm SM}=\mathrm{SU}(3)_c\otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$. One may have them transforming in the same way as the ordinary quarks and leptons (usually including the analog of the right-handed neutrino), or one may introduce

$$F_L \sim (R,1,2)(0),\quad F_{1R}\sim (R,1,1)(1)\ ,\quad F_{2R}\sim (R,1,1)(-1) \tag{1}$$

under $G=G_{\rm TC}\otimes G_{\rm SM}$, where technifermions transform under the R representation of $G_{\rm TC}$. The latter possibility is attractive because it contains fewer degrees of freedom than the former. Indeed, ignoring technicolor, the spectrum in Eq. (1) defines the simplest, anomaly-free, nontrivial chiral representation under $G_{\rm SM}$, and so it would perhaps not be surprising if nature made use of this possibility somewhere. One should note that this spectrum yields (confined) charge $\pm\frac{1}{2}$ fermions.

Usually these particles are postulated in an *ad hoc* manner, leaving it as a mystery as to why ordinary fermions should have different $G_{\rm SM}$ properties from technifermions. In this Brief Report we will construct an extension of the SM that incorporates charge $\pm\frac{1}{2}$ technifermions in a natural way.

Before describing the model, it is necessary to address the issue of mass generation in technicolor theories. It is well known that technifermion condensation is not sufficient to generate quark and lepton masses, due to a residual global chiral symmetry. New physics is required to break this symmetry and generate realistic fermion masses without introducing new problems.

The nature of this new physics is an unresolved issue. The simplest candidate, extended technicolor (ETC), usually has phenomenological problems due to unacceptably large flavor-changing neutral processes.[3] Recently, "walking technicolor" theories have engendered new hope that a realistic ETC theory may exist.[4,5] We will not address these difficult and important issues in this Brief Report. Instead we will follow other authors[5–7] by adopting an intermediate position between the exclusive use of elementary spin-zero fields for symmetry breaking and fermion mass generation as in the SM, and the hypothetical realistic ETC-like theory free of all elementary spin-zero particles. Such particles will *not* be used for electroweak symmetry breaking, but they will be used to perform the symmetry breaking of a new gauge group at a relatively high scale, and the ordinary spin-zero doublet (with a *zero* VEV) will be used to generate quark and lepton masses, as in Simmons.[6] One may view these elementary spin-zero particles as "shorthand" for new and unknown physics which we hypothesize to exist.

We now describe the model.[8] The gauge group is

$$G=\mathrm{SU}(N)\otimes \mathrm{SU}(3)_c\otimes \mathrm{SU}(2)_L\otimes \mathrm{U}(1)_X\ , \tag{2}$$

under which three (or more) generations of fermions transform as

$$f_L \sim (N,1,2)(x_1), \quad f_{1R} \sim (N,1,1)(x_2) ,$$
$$f_{2R} \sim (N,1,1)(x_3), \quad q_L \sim (1,3,2)(x_4) , \tag{3}$$
$$q_{1R} \sim (1,3,1)(x_5), \quad q_{2R} \sim (1,3,1)(x_6) .$$

The fields f will contain the ordinary leptons and the technifermions, while the q's will be ordinary quarks. The Abelian group $U(1)_X$ is *not* weak hypercharge, and the charges $x_1, \ldots, x_6$ are *a priori* undetermined.

We now introduce the standard spin-zero doublet in the manner of Simmons:[6,9]

$$\phi \sim (1,1,2)(1) . \tag{4}$$

Note that we have set the arbitrary normalization factor for X so that the X charge of ϕ is 1. We demand that the standard Yukawa Lagrangian

$$L_{\rm Yuk} = \lambda_1 \bar{f}_L f_{1R} \phi + \lambda_2 \bar{f}_L f_{2R} \tilde{\phi} + \lambda_3 \bar{q}_L q_{1R} \phi + \lambda_4 \bar{q}_L q_{2R} \tilde{\phi} + \text{H.c.} \tag{5}$$

be invariant under G. This implies that

$$x_2 = x_1 - 1, \quad x_3 = x_1 + 1 ,$$
$$x_5 = x_4 - 1, \quad x_6 = x_4 + 1 . \tag{6}$$

This pattern of X charges is anomaly-free for $[\mathrm{SU}(N)]^2\mathrm{U}(1)_X$, $[\mathrm{SU}(3)_c]^2\mathrm{U}(1)_X$, and $[\mathrm{U}(1)_X]^3$ for all values of x_1 and x_4. The remaining nontrivial gauge anomaly $[\mathrm{SU}(2)_L]^2\mathrm{U}(1)_X$ is zero provided

$$x_4 = -\frac{N x_1}{3} . \tag{7}$$

The spectrum is now

$$f_L \sim (N,1,2)(x), \quad f_{1R} \sim (N,1,1)(x-1) ,$$
$$f_{2R} \sim (N,1,1)(x+1), \quad q_L \sim (1,3,2)\left[-\frac{Nx}{3}\right] , \tag{8}$$
$$q_{1R} \sim (1,3,1)\left[-\frac{Nx}{3}-1\right], \quad q_{2R} \sim (1,3,1)\left[-\frac{Nx}{3}+1\right] ,$$

where $x \equiv x_1$ is as yet undetermined.

We now break the gauge group G to one which contains the technicolor group and the SM group; i.e.,

$$G \to \mathrm{SU}(N-1)_{\rm TC} \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y . \tag{9}$$

To do this we introduce an elementary Higgs field χ to break

$$\mathrm{SU}(N) \otimes \mathrm{U}(1)_X \to \mathrm{SU}(N-1)_{\rm TC} \otimes \mathrm{U}(1)_Y .$$

The fields f separate into singlets under $\mathrm{SU}(N-1)_{\rm TC}$ (the technicolor group), which we intend to identify with ordinary leptons, and technifermions transforming under the fundamental representation of technicolor. Interestingly, this Higgs field can play a dual role, for it can also give a large Majorana mass to right-handed neutrinos. Thus the presence of a large Majorana mass, necessary for the assumed seesaw mechanism[10] to work, is correlated with a high symmetry-breaking scale for the ETC-like group $\mathrm{SU}(N)$. Let us choose the right-handed neutrino to reside inside f_{2R}:

$$L'_{\rm Yuk} = h \bar{f}^{\,c}_{2R} f_{2R} \chi + \text{H.c.} , \tag{10}$$

where the Higgs field

$$\chi \sim (\square\!\square^*, 1, 1)(-2x-2) . \tag{11}$$

A nonzero VEV for χ indeed breaks $\mathrm{SU}(N)$ down to $\mathrm{SU}(N-1)_{\rm TC}$ as well as giving the $\mathrm{SU}(N-1)_{\rm TC}$ singlet part of f_{2R} (i.e., ν_R) a large Majorana mass.

From the symmetry breaking induced by χ we can identify the hypercharge. Consider

$$Y = X + \alpha T , \tag{12}$$

where T refers to the diagonal generator of $\mathrm{SU}(N)$ which is broken by the VEV for χ. We normalize it so that $T = \mathrm{diag}(N-1, -1, \ldots, -1)$ in the fundamental representation. α is obtained by demanding that $\langle \chi \rangle$ be annihilated by Y. Since

$$\square\!\square^* \to \square\!\square^*(2) \oplus \square^*(2-N) \oplus \underline{1}(2-2N) \tag{13}$$

under $\mathrm{SU}(N) \to \mathrm{SU}(N-1)_{\rm TC} \otimes \mathrm{U}(1)_T$ for our normalization of T it follows that

$$\alpha = \frac{x+1}{1-N} . \tag{14}$$

The next step is to use the TC mechanism to break the SM gauge group in the usual way[11] so that $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_Q$ where

$$Q = I_3 + \beta Y . \tag{15}$$

It is assumed that $\mathrm{SU}(N-1)_{\rm TC}$ induces the condensates

$$\langle \bar{F}^+_L F_{2R} \rangle, \quad \langle \bar{F}^-_L F_{1R} \rangle \neq 0 , \tag{16}$$

where F_L, F_{1R}, and F_{2R} are the components of f_L, f_{1R}, and f_{2R}, respectively, which transform under $\mathrm{SU}(N-1)_{\rm TC}$. The $(\pm)$ superscript on F_L denotes the $I_3 = \pm\frac{1}{2}$ component thereof. β is obtained by requiring that the technifermion condensates are neutral under Q. These are neutral under Q provided

$$\beta = \tfrac{1}{2} . \tag{17}$$

So our electric charge candidate is

$$Q = I_3 + \frac{1}{2}\frac{x+1}{1-N} T + \frac{X}{2} . \tag{18}$$

The Q charges of the fermions in the theory are

$$Ql_L=\begin{bmatrix}0\\-1\end{bmatrix},\quad QF_L=\begin{bmatrix}\frac{1}{2}-\frac{1}{2}\frac{1+Nx}{1-N}\\-\frac{1}{2}-\frac{1}{2}\frac{1+Nx}{1-N}\end{bmatrix},$$

$$Ql_{1R}=-1,\quad QF_{1R}=\frac{1}{2}\frac{2+N(x-1)}{N-1},$$

$$Ql_{2R}=0,\quad QF_{2R}=\frac{1}{2}\frac{N(x+1)}{N-1}, \tag{19}$$

$$Qq_L=\begin{bmatrix}\frac{1}{2}-\frac{Nx}{6}\\-\frac{1}{2}-\frac{Nx}{6}\end{bmatrix},\quad Qq_{1R}=-\frac{1}{2}\left[\frac{Nx}{3}+1\right],$$

$$Qq_{2R}=\frac{1}{2}\left[-\frac{Nx}{3}+1\right].$$

Note that the charges of the ordinary leptons l_L, l_{1R}, and l_{2R} are completely determined, while the rest depend on the unknowns N and x.

We have used the conditions of mass generation and anomaly cancellation to fix the electric charges of the fermions in terms of the parameters x,N. We now make the observation that if

$$x=-\frac{1}{N} \tag{20}$$

then the ordinary quarks and leptons have the correct electric charges and the technifermions have electric charges $\pm\frac{1}{2}$. Explicitly we find

$$QF_L=\begin{bmatrix}\frac{1}{2}\\-\frac{1}{2}\end{bmatrix},\quad QF_{1R}=-\tfrac{1}{2},\quad QF_{2R}=\tfrac{1}{2},$$
$$Qq_L=\begin{bmatrix}\frac{2}{3}\\-\frac{1}{3}\end{bmatrix},\quad Qq_{1R}=-\tfrac{1}{3},\quad Qq_{2R}=\tfrac{2}{3}. \tag{21}$$

Hence we have shown that in our theory the electric charges of the ordinary fermions are necessarily connected with the charges ($\pm\frac{1}{2}$) of the technifermions, for any value of N.

The residual 1 parameter (x) freedom of our model indicates that this theory has the same problem accounting for electric charge quantization as does the SM with right-handed neutrinos.[12] As in the latter theory, one may explore new physics in an attempt to fix the free parameter to the value given in Eq. (20).[13] We will not pursue this remaining issue in this paper.

In conclusion, we have shown how charge $\pm\frac{1}{2}$ technifermions can be automatically incorporated into a theory based on an ETC-like group SU(N). Technicolor is identified via the symmetry breaking SU(N) $\to$SU$(N-1)_{\rm TC}$. The generator T is instrumental in the definition of electric charge, thereby allowing leptons to have standard charges, even though the technifermions have exotic half-integral charges. As in other technicolor theories, fermion mass generation remains an open problem, although we were able to model the required new physics through the agency of "effective" elementary spin-zero fields.

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[8] This model and the subsequent analysis describes our basic ideas. There are perhaps more elegant ways of implementing these ideas that are, however, less accessible. For example, consider a model that involves quark-lepton symmetry [R. Foot and H. Lew, Phys. Rev. D **41**, 3502 (1990); Nuovo Cimento (to be published)] and assume the existence of the large color group SU(5) [R. Foot and O. F. Hernandez, Phys. Rev. D **41**, 2283 (1990)]. Then the gauge group is $SU(5)_q\otimes SU(5)_1\otimes SU(2)_L\otimes U(1)$, with fermions transforming under this group as follows:

$$f_L\sim(1,5,2)(y_1),\quad (Q_L)^c\sim(5,1,2)(y_1),$$
$$e_R\sim(1,5,1)(y_2),\quad (u_R)^c\sim(5,1,1)(y_2),$$
$$\nu_R\sim(1,5,1)(y_3),\quad (d_R)^c\sim(5,1,1)(y_3).$$

It can be shown that when the appropriate Yukawa terms exist the theory breaks to an effective theory with gauge group

$$SU(3)_c\otimes SU(2)'\otimes SU(4)_{TC}\otimes SU(2)_L\otimes U(1)_Y.$$

This low-energy theory contains the ordinary fermions (with the usual hypercharges) and technifermions [with the left-handed fields in $Y=0$ $SU(2)_L$ doublets and right-handed fields in $Y=\pm 1$ $SU(2)_L$ singlets], provided $y_3=-4y_1$. When the technifermions condense, the gauge group breaks dynamically to $SU(3)_c \otimes SU(2)' \otimes SU(4)_{TC} \otimes U(1)_Q$.

[9]Observe that the leptons will gain mass via the standard ETC mechanism due to the gauge bosons in the coset space $SU(N)/SU(N-1)$. However for the standard reasons these gauge bosons will also induce flavor-changing neutral currents (FCNC's). In order to have the FCNC's within experimental bounds typically requires a negligible contribution to the masses of the ordinary leptons (see Ref. 3). We therefore employ the mass generation mechanism studied by Simmons in Ref. 6, which utilizes a tadpolelike Feynman diagram.

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[11]For three generations of fermions the model has a global $SU(6)_L \otimes SU(6)_R$ symmetry if all interactions other than TC are neglected. This global symmetry is spontaneously broken to $SU(6)_{L+R}$ when TC becomes strong and hence results in 35 Goldstone bosons, three of which get absorbed by the Higgs mechanism. The remaining 32 are, however, pseudo-Goldstone bosons since the global symmetry is explicitly broken by effective four-Fermi interactions induced by SM gauge, ETC-like, and scalar-exchange-type interactions. See Ref. 2 for further details.

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