Quarks and leptons are taken as composites of spin-1/2 fermions $F$ with charges $\pm 1/2$ and spinless bosons $S$ with charges $-1/6$ and $+1/2$. The lightest families of quarks and leptons are identified as linear combinations of $F\bar{S}$, $FSSS$, and $FSS\bar{S}$, bound into singlets of a superstrong $SU(4)$ gauge group. Higgs bosons are made of $F\bar{F}$. Additional predicted states in the TeV mass range include spin-1 $F\bar{F}$ states with isospins $I = 0$ and 1 and an exotic family of quarks with charges $Q = (-4/3, -1/3, 2/3, 5/3)$ and leptons with charges $Q = (-2, -1, 0, 1)$. 
The observed quarks and leptons form three nearly complete, identical families, consisting of \((u,d,e^-)\), \((c,s,\mu^-)\), and \((t,b,\tau^-,\nu_\tau)\) and their corresponding antiparticles. Only the top quark \(t\) and the \(\tau\) neutrino \(\nu_\tau\) remain to be discovered.

This pattern suggests the beginning of a composite structure, reminiscent of the periodic table of the elements. However, up to now no self-consistent model of composite quarks and leptons has been found. The difficulty has been construction of nearly pointlike objects with masses small compared to the compositeness scale.\(^1\) It has been proposed that a chiral symmetry protects quarks and leptons from acquiring large masses. However, in any vectorlike theory for the force which binds constituents into quarks and leptons, the chiral symmetry is expected to be spontaneously broken,\(^2\) so that the lightest states are Nambu-Goldstone bosons rather than fermions. The chiral symmetry is then unavailable for protection of fermion masses.

In the present Letter we propose a structure of quarks and leptons which may circumvent the restrictions of Ref. 2. The lowest states indeed are Nambu-Goldstone bosons, but they correspond to Higgs particles, and are absorbed into longitudinal components of electroweak gauge bosons. Fermion masses are generated only at the level of electroweak symmetry breaking. Gauge bosons of a group containing at least the standard \(SU(3)\times SU(2)_L \times U(1)_Y\) model are assumed to be elementary.

The electric charge \(Q\) of a quark or lepton may be written\(^3\)

\[
Q = I_{3L} + I_{3R} + (B - L)/2
\]  

where \(I_{3L}\) and \(I_{3R}\) are the third components of left- and right-handed isospin, \(B\) is the baryon number, and \(L\) is the lepton number. Since the handedness of quarks and leptons is correlated with their \(I_{3L}\) and \(I_{3R}\) values, we choose their only spin-1/2 constituents to be fermions with \(Q = \pm 1/2\), letting the contribution \((B - L)/2\) to \(Q\)
be carried by scalar particles. The result is a model with Dirac fermions

\[ F = (U, D) : \quad Q = (1/2, -1/2) \]  

(2)

and scalars

\[ S = (S_1, S_2, S_3, S_4) : \quad Q = (-1/6, -1/6, -1/6, 1/2) \]  

(3)

Weak \( SU(2) \) [i.e., \( SU(2)_L \)] acts on the fermions \( F \), so that doublets of \( SU(2)_L \) are \((U, D)_L\) and \((D, -U)_R\), while the remaining states \( U_R, D_R, \bar{D}_R, \) and \(-\bar{U}_R\) are singlets of \( SU(2)_L \). Color \( SU(3) \) acts on the first three of the four scalars \( S_i \) and thus is automatically vectorial for composite states involving \( S_i \). Color \( SU(3) \) can be embedded in an \( SU(4)_c \), with lepton number as the fourth color.\(^4\)

The description of quarks and leptons as \( FS \) bound states then reproduces the formula (1), and gives the correct set of charges and other quantum numbers.\(^4,5\) A variant of the model envisions \( S \) as composed of a fermion pair.\(^6\)

A further advantage of choosing fermions \( F \) with charges \( \pm 1/2 \) is that the lowest-lying spinless \( FF \) bound states are candidates for Higgs bosons. Thus, we envision dynamical electroweak symmetry breaking.\(^7\) The states \( U\bar{D}, D\bar{U}, \) and \( (U\bar{U} - D\bar{D})/\sqrt{2} \) are absorbed into the electroweak gauge bosons \( W^+, W^- \) and \( Z \) as longitudinal components, while the fourth \( [(U\bar{U} + D\bar{D})/\sqrt{2}] \) remains a particle in the spectrum. In analogy with the fate of the \( \eta \) in QCD,\(^8\) this particle should acquire a mass characteristic of the electroweak symmetry breaking scale. No anomaly is present in the coupling between \( (U\bar{U} - D\bar{D})/\sqrt{2} \) and a pair of photons because \( Q_U^2 - Q_D^2 = 0.\)\(^6,9\)

Vector \( FF \) states are also expected. If we classify them according to \( I = I_L + I_R, \) they consist of an \( I = 1 \) state \( \rho_T \) and an \( I = 0 \) state \( \omega_T \). The suffix stands for TeV, their expected mass scale.\(^10,11\)

The minimal dynamical electroweak symmetry scheme described above is to be
contrasted with more elaborate ones in which a further interaction is postulated in order to give quarks and leptons masses. The price of such schemes seems to be the presence of numerous unwanted spinless bosons and flavor-changing neutral currents.

So far the superstrong force that binds constituents into quarks and leptons has not been specified. We have found that an $SU(4)$-invariant interaction, becoming strong at the TeV scale as its coupling is evolved via the renormalization group from higher mass scales, is capable of giving rise to three families of quarks and leptons. We shall call the gauge group of this interaction $SU(4)_T$.

Each of the fermions $F$ and scalars $S$ in (2) and (3) is then taken to transform as a quartet $(4_T)$ of $SU(4)_T$. We consider fermionic states which can be formed as singlets of $SU(4)_T$. Two such states are

\[ f_1 \equiv F \bar{S} ; \quad f_2 \equiv F(SSF)_{4_T} \]  

in a configuration where all relative orbital angular momenta vanish. Both of these states transform as ordinary quarks and leptons. In particular, the three scalars in $FSSS$ are required by Bose statistics to have the same symmetry under $SU(4)_c$ as they do under $SU(4)_T$, so they transform as $\bar{S}^m \sim \epsilon^{mijk} S_i S_j S_k$, i.e. as a $4^*$ of $SU(4)_c$.

The mixing of the families $f_1$ and $f_2$ can take place if there is an operator transforming as $(SSS)_{1_T}$, as illustrated in Fig. 1(a). This operator will also be an $SU(4)_c$ singlet if there are no relative angular momenta, by Bose statistics. In turn, it can mix $f_2$ with states of the form

\[ f_3 = FSS\bar{S} \]  

where the $SS\bar{S}$ state is in a $(4^*_T, 4^*)$ representation, as shown in Fig. 1(b). The states (4) and (5) are the only singlets of $SU(4)_T$ with a single $F$ and one or three scalars. Thus we identify linear combinations of $f_1$, $f_2$, and $f_3$ as the three lowest-lying
quark and lepton families. An operator transforming as \((S\bar{S})_{1\sigma}\) would mix \(f_3\) with \(f_1\) [Fig. 1(c)].

The spinless \((S\bar{S})_{1\sigma}\) states form a rich spectrum of predicted exotic particles. They consist of a neutral color octet, a color triplet with charges 2/3, a color antitriplet with charges \(-2/3\), and two neutral color singlets. The charged colored scalars are leptoquarks, coupling to a charged lepton and a charge \(\pm 1/3\) quark or a neutrino and a charge \(\pm 2/3\) quark. They have to be quite heavy (\(\gtrsim 100\) TeV) in order to suppress decays like \(K_L \to \mu e\). This is also true of the gauge bosons which become massive when \(SU(4)_c\) breaks down to \(SU(3)_c \times U(1)_{B-L}\), if \(SU(4)_c\) is a gauged symmetry. If a very large condensate \((S_1\bar{S}_1 + S_2\bar{S}_2 + S_3\bar{S}_3 - 3S_4\bar{S}_4)/\sqrt{12} \neq 0\) is responsible for breaking \(SU(4)_c\) to \(SU(3)_c \times U(1)\), the leptoquark \(S\bar{S}\) bosons could be absorbed into longitudinal components of \(SU(4)_c/[SU(3)_c \times U(1)]\) gauge bosons and thus be removed from the low-lying spectrum.

The absence of flavor-changing neutral currents at zero momentum transfer is guaranteed by the orthogonality of wave functions of the mixtures of \(FS\bar{S}, FSSSS,\) and \(FS\bar{S}\bar{S}\bar{S}\) that make up the first three quark and lepton families. [A strong constraint on the compositeness scale may arise from the apparent suppression of the decay \(\mu \to e\gamma\), but a detailed calculation is required for the present model.] Since charge-changing weak transitions involve the interchange \(U \leftrightarrow D\), any difference in residual interactions of a \(U\) and \(D\) with the scalars can lead to non-trivial angles in the Cabibbo-Kobayashi-Maskawa matrix elements. This behavior has been illustrated recently in a different context.\(^{17}\)

A Dirac mass term for the three quark and lepton families just constructed will violate \(SU(2)_L \times U(1)_Y\), and thus is forbidden until \(SU(2)_L \times U(1)_Y\) is violated by the vacuum expectation value of the combination \((U\bar{U} + D\bar{D})/\sqrt{2}\). The actual magnitude
of the Dirac mass terms for different quarks and leptons will depend upon their Yukawa couplings to this combination, as well as the mixing of different families mentioned earlier. A detailed calculation of $F\bar{S}$, $FSSS$ and $F\bar{S}\bar{S}$ binding is required to see if the model can yield sufficiently light quarks and leptons. One could imagine performing such a calculation using lattice methods or analogues of QCD sum rules, for example.

Small left-handed neutrino masses in the present model arise from large Majorana masses for right-handed neutrinos. This may be achieved if a combination $<N_R N'_R>$ acquires a large vacuum expectation value, where $N_R$ is a right-handed neutrino. Such a condensate also breaks $SU(2)_R \times U(1)_{B-L}$ down to $U(1)_Y$ if we have chosen to gauge such symmetries separately, where $Y = 2I_3R + B - L$ is weak hypercharge. The number of different terms of such type might govern the number of quark-lepton families containing very light neutrinos, for which $Z$ decays imply $N_\nu = 3.04 \pm 0.04$. One could tolerate the presence of more than three families of quarks and leptons if all members of the additional families including the neutrinos had ordinary Dirac masses of at least $M_Z/2$.

Four $SU(4)_T$ quartets can also be coupled totally antisymmetrically into singlets to form families consisting of $FFSS$, $FFFS$, and $FFFF$. We briefly recount the expected properties of the S-wave states.

In the $FFSS$ states, the $SS$ subsystem must be in a $6_T$ (antisymmetric) representation. Because of Bose statistics, the $SS_{6_T}$ pair must be antisymmetric in $SU(4)_c$, and so will consist of a color triplet with charge $-1/3$ and a color antitriplet with charge $1/3$. The $FF$ pair is also in a $6_T$ representation, and so must be symmetric in its remaining degrees of freedom. Thus, it consists of $I = J = 1$ and $I = J = 0$ states, just as do the nonstrange quarks in the $\Sigma$ and $\Lambda$ hyperons. The $FFSS$ states then
consist of spin-1 color triplets with charges $2/3, -1/3,$ and $-4/3$ and antitriplets with charges $4/3, 1/3,$ and $-2/3,$ and spin-0 triplets with charge $-1/3$ and antitriplets with charge $1/3.$ Since the $SSSS$ operator mentioned earlier can mix $FFSS$ with $FFSS$ (for example), the $FFSS$ states have many features in common with diquarks. As a result, their signatures in high-energy hadron collisions may not be very distinctive.

In the $FFFS$ states, the subsystem $(FFF)_4$ must be totally symmetric in the product of its isospin $x$ spin $[(I, J)]$ variables. This is also true of the lowest baryonic quark-model states, which consist of $N(1/2, 1/2)$ and $\Delta(3/2, 3/2)$ (for nonstrange states). Thus, we expect the $FFF$ states to form an isospin doublet with charges $Q = \pm 1/2$ and spin $1/2,$ and an isospin quartet with charges $Q = (3/2, 1/2, -1/2, -3/2)$ and spin $3/2.$ The corresponding $FFFS$ states are then:

$$J = 1/2: \quad \text{Quarks with } Q = (2/3, -1/3)$$
$$\quad \text{Leptons with } Q = (0, -1), \quad (6a)$$

$$J = 3/2: \quad \text{Quarks with } Q = (5/3, 2/3, -1/3, -4/3)$$
$$\quad \text{Leptons with } Q = (1, 0, -1, -2). \quad (6b)$$

To estimate masses, we proceed in analogy with the constituent quark model, multiplying by a scale\(^{11}\) of $\sim 2650 = (246 \text{ GeV}/93 \text{ MeV}),$ or $\sqrt{3}/4$ times that if large-$N$ scaling arguments apply\(^{16}\) to the comparison of $SU(4)_T$ and $SU(3)_c.$

The expected mass of a "constituent $F$" is then about 700 to 800 GeV. Binding to $\bar{S}$ has to be responsible for a negative shift of about this same amount. Correspondingly, one expects a "constituent $FFF$" to have a mass of $2 - 2.5$ TeV for spin $1/2$ and $2.8 - 3.3$ TeV for spin $3/2.$ The states $(6a)$ then should lie between 1.3 and 1.7 TeV, while $(6b)$ should lie between 2.1 and 2.5 TeV.

The $FFFF$ states are found, by arguments similar to those presented for the $FFF$ states, to consist of states with $(I, J) = (2, 2), (1, 1),$ and $(0, 0).$ Any scalar
operator $FFFF$, which could contribute to proton decay via the diagram of Fig. 2, must be very weak or absent.

Orbital excitations of the lowest-lying states are expected. If experience with ordinary hadrons is any guide, we expect them to lie about a TeV above the corresponding $S$-wave states.

The present model is not supersymmetric, since the fermions $F$ and bosons $S$ have different charges. However, they do have equal numbers of degrees of freedom. The spectrum of bound states involving $F$ and $S$ then should display an equality in numbers of fermion and boson states.

To conclude, we have proposed that the building blocks of quarks and leptons are sets of fermions $F$ and scalars $S$, both transforming as quartets of a superstrong $SU(4)$ which binds them into singlets in states of zero relative orbital angular momenta. The three observed families are combinations of $FSSF$, $FSSS$, and $FSSS$. Higgs bosons are spinless $F\bar{F}$ states, all but one of which are absorbed into longitudinal components of $W^+$, $W^-$, and $Z$. A rich spectrum of exotic states is predicted to lie in the 1-3 TeV region, including spin-1 $F\bar{F}$ mesons and quarks and leptons with unusual charges.

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4. Pati and Salam, Ref. 3.


FIGURE CAPTIONS

FIG. 1. Diagrams denoting mixing of families. Solid lines denote fermions $F$; dashed lines stand for scalars $S$. Arrows from left to right stand for members of $4_{\bar{T}}$; arrows from right to left stand for $4_{\bar{T}}$ members. (a) mixing of $F\bar{S}$ and $FSSS$ states; (b) mixing of $FSSS$ and $FS\bar{S}\bar{S}$; (c) mixing of $FSS\bar{S}$ and $F\bar{S}$. 

FIG. 2. Diagram contributing to proton decay.
Figure 1

Figure 2