Unifiable Chiral Color with Natural Glashow-Iliopoulos-Maiani Mechanism

Paul H. Frampton[a] and Sheldon L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, and
Department of Physics, Boston University, Boston, Massachusetts 02215
(Received 25 March 1987)

A unique and appealing chiral-color theory is presented. It involves five fermion families, four light neutrinos, and several more exotic states. The Glashow-Iliopoulos-Maiani mechanism is preserved and the theory is embedded in the unifying group $[SU(4)]^6$.

PACS numbers: 12.10.Dm, 11.30.Rd

In an earlier paper,[1] we propose an alternative to the standard model involving chiral color. The gauge group of the strong, weak, and electromagnetic interactions is taken to be

$$R = SU(3)_L \otimes SU(3)_R \otimes SU(2)_L \otimes U(1), \qquad (1)$$

rather than $SU(3)\otimes SU(2)\otimes U(1)$. The chiral-color group $SU(3)_L \otimes SU(3)_R$ breaks down to its diagonal subgroup $SU(3)_C$ at a mass scale comparable to that of electroweak symmetry breaking. Chiral-color models demand the existence of a wide variety of new particles including exotic fermions and spinless mesons with color and charge. A specific prediction of *any* such model is the existence of the *axigluon*, a color octet of electrically neutral gauge bosons with mass not greater than several hundred gigaelectronvolts.

In Ref. 1, we present five illustrative chiral-color models based upon different choices of the anomaly-free fermion representation. In this paper, we focus upon what we now regard as the most promising realization of chiral color. We base our choice upon the following constraints that are reasonable to impose upon an alternative to the standard model which is to recapture the latter's past triumphs:

I. The light fermions form a real representation of the exact QCD-QED group $SU(3)_C \otimes U(1)_Q$. This is obligatory for any sensible theory.

II. There are no triangle anomalies among the currents coupled to the gauge bosons of R. This yields two constraints upon the fermion representation, above and beyond those of the standard model, which must be satisfied if the theory is to be renormalizable.

III. The electric charges of all fundamental fields are such that all color-neutral configurations have integer charge. There must be no isolable fractionally charged particles.

IV. No fundamental field surviving at low energy carries electric charge greater than 1. This technical assumption excludes certain bizarre and unpalatable possibilities. Axioms III and IV imply that all quarks [i.e., fermons transforming as **3**'s of $SU(3)_C$] carry electric charges $\frac{2}{3}$ or $-\frac{1}{3}$. [A variation of Mark II (Ref. 1) requiring a quark of charge $-4\frac{1}{3}$ is thereby excluded.]

V. The left-handed quarks comprise N weak doublets, while the right-handed quarks are all weak singlets. This ensures that the couplings of Z^0 are flavor diagonal whatever the form of the quark mass matrix. This axiom is violated by Mark II of Ref. 1. In that model, the Glashow-Iliopoulos-Maiani (GIM) mechanism is undone by Z^0 couplings.

VI. All left-handed quarks are triplets under $SU(3)_L$ and singlets under $SU(3)_R$. Conversely, all right-handed quarks are triplets under $SU(3)_R$ and singlets under $SU(3)_L$. This is the gist of any naive implementation of chiral color and ensures that axigluon couplings are parity conserving and purely axial vector. More importantly, axiom VI guarantees that they are flavor diagonal. Marks I, III, and IV of Ref. 1 violate this axiom. For these models, potentially serious violations of the GIM cancellation of flavor-changing neutral currents can be induced by axigluon exchange. Axioms V and VI together ensure that the Glashow-Weinberg criterion[2] may be satisfied for the Higgs-boson couplings: that no more than one Higgs boson need be introduced to give quarks of a given charge their masses, thus ensuring the absence of GIM-violating effects mediated by Higgs bosons.

Except for Mark V, all of the models proposed in Ref. 1 violate one or another of the preceding axioms and present the threat of sizable GIM violation. These effects can be controlled by judicious choice of the fermion mass matrix with generalized mixing angles no smaller than those already observed in nature. We cannot logically exclude models which violate our axioms. Nonetheless, it would seem preferable to search for a theory in which the GIM mechanism is exact and automatic rather than approximate and imposed.

VII. Our final axiom is the requirement that the chiral-color theory, like its predecessor, should be embeddable within a unified theory involving a single gauge coupling constant. The notion of grand unification is too attractive to be lightly abandoned.

One and only one model described in Ref. 1 satisfies all of the above axioms. Furthermore, we are unable to identify any acceptable model distinct from Mark V. Under $(SU(3)_L, SU(3)_R, U(1)_Q)$, the fermion representation which satisfies all seven axioms consists of the following left-handed chiral fields. There are *five* quark families, including the five weak doublets,

$$5[(\mathbf{3},\mathbf{1},\tfrac{2}{3})\oplus(\mathbf{3},\mathbf{1},-\tfrac{1}{3})],$$

and five associated charged leptons with their left-handed neutrinos. These neutrinos do not have singlet partners in the low-energy world. They are massless except for see-saw effects of order M^{-1} where M is the unification mass, and except for a novel and curious mechanism we discuss anon.

The following Higgs bosons must be introduced to give masses to quarks and charged leptons. [Our notation for scalar mesons designates transformation behavior under $(\mathrm{SU}(3)_L,\mathrm{SU}(3)_R,\mathrm{SU}(2)_L)$.] $\phi(\mathbf{3}^*,\mathbf{3},\mathbf{2})$ with $Q=0,1$ gives masses to the $Q=\frac{2}{3}$ quarks, $\phi'(\mathbf{3}^*,\mathbf{3},\mathbf{2})$ with $Q=-1,0$ gives masses to the $Q=-\frac{1}{3}$ quarks, and $\phi(\mathbf{1},\mathbf{1},\mathbf{2})$ gives masses to charged leptons. Many of these particles must survive in the low-energy world including spinless color octets with and without electric charge.

There must exist additional fermions with nontrivial transformation properties under chiral color if all anomalies are to cancel, including those cubic and quadratic in the generators of chiral color. The following simple systems of exotic fermions suffice[3]: a "quix" of fermions with "conventional" electric charge,

$$(\mathbf{6}^*,\mathbf{1},-\tfrac{1}{3})\oplus(\mathbf{1},\mathbf{6},+\tfrac{1}{3}),$$

and a "dichromatic" fermion multiplet with no electric charge,

$$(\mathbf{3}^*,\mathbf{3},0).$$

The quix can bind to quarks to produce novel and observable hadrons. It must acquire a hard mass to avoid the appearance of an all too visible axion. Two mass-generating mechanisms suggest themselves: A $\phi(\mathbf{6},\mathbf{6}^*,\mathbf{1})$ with a vacuum expectation value (VEV) can be introduced, or alternatively, a system of VEV-less scalar mesons $\phi(\mathbf{3},\mathbf{1},\mathbf{2})\oplus\phi(\mathbf{1},\mathbf{3}^*,\mathbf{1})$ can generate a quix mass at one loop. To obtain a sensibly large quix mass, these scalar quarks must reside in the low-energy world and be ingredients of observable "hadrons." The latter mechanism may be preferable since it leads to quix decay in addition to a quix mass:

$$(\mathbf{6}^*,\mathbf{1})\to\phi^*(\mathbf{3},\mathbf{1},\mathbf{2})+\text{antiquark},$$

$$(\mathbf{1},\mathbf{6})\to\phi(\mathbf{1},\mathbf{3},\mathbf{1})+\text{quark}.$$

If the quix is sufficiently heavier than the scalar quark, its decay is rapid. Otherwise, it will be long lived, depending upon the decay of a virtual ϕ into a quark and an antineutrino. This process relies upon the see-saw mechanism and is suppressed by M^{-2} in rate. Whatever their relative masses, either the quix or the scalar quark or both will have a lifetime of order of the *square* of the unification mass: short cosmologically, but long on the time scale of any accelerator experiment. Here is a fine possibility for new physics at high energy.

The dichromatic $(\mathbf{3}^*,\mathbf{3})$ of fermions acquires its mass via the VEV of an electronweak neutral $\phi(\mathbf{3}^*,\mathbf{3},\mathbf{1})$. It follows that the "quone" [the color-neutral fermion in the $(\mathbf{3}^*,\mathbf{3})$] has twice the mass of the octet "queight." Queight and quone are coupled to quarks and leptons via Yukawa couplings to $\phi(\mathbf{3},\mathbf{1},\mathbf{2})$ and to $\phi(\mathbf{1},\mathbf{3}^*,\mathbf{1})$. Thus, the queight forms unstable hadrons. The VEV of $\phi(\mathbf{3},\mathbf{1},\mathbf{2})$ generates a "Dirac mass" linking the quone to one linear combination of the five neutrino states. One of the five neutrinos acquires a large mass and a short lifetime. How large and how short we cannot say. The validity of universality for electrons, muons, and tau leptons suggests that the heavy neutrino is primarily associated with the two heavier and yet unseen charged leptons of families four and five.

It remains for us to show that our model satisfies axiom VII above, that it can be embedded within a unified theory with a single coupling constant.

As mentioned briefly in Ref. 1, the required unification group is $G=[\mathrm{SU}(4)]^6$. The way in which the gauge group R is embedded in G is as follows.

We embed $\mathrm{SU}(3)_L$ and $\mathrm{SU}(3)_R$, respectively, into two of the SU(4) factors. $\mathrm{SU}(2)_L$ is embedded twice into one SU(4) [denoted $\mathrm{SU}(4)_{2,2}$] as $\left(\begin{smallmatrix}\sigma & 0\\ 0 & \sigma\end{smallmatrix}\right)$ and once into another SU(4) [denoted $\mathrm{SU}(4)_2$ as $\left(\begin{smallmatrix}\sigma & 0\\ 0 & 0\end{smallmatrix}\right)$. The final two SU(4) groups are completely broken. The unbroken electric-charge operator lies partially in each of the six SU(4) groups:

$$Q=\begin{pmatrix}\frac{1}{6} & & & \\ & \frac{1}{6} & & \\ & & \frac{1}{6} & \\ & & & -\frac{1}{2}\end{pmatrix}_{\mathrm{SU}(4)_{L,R}},\quad Q=\frac{1}{2}\begin{pmatrix}1 & & & \\ & -1 & & \\ & & 1 & \\ & & & -1\end{pmatrix}_{\text{otherwise}}$$

The fermions fall into eighteen irreducible representations of $\{\mathrm{SU}(4)_L,\mathrm{SU}(4)_{2,2},\mathrm{SU}(4),\mathrm{SU}(4)_R,SU(4),\mathrm{SU}(4)_2\}$ as follows:

$$\begin{aligned}&2[(\mathbf{4},\mathbf{4}^*,\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{4}^*,\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{4}^*)]\oplus(\mathbf{1},\mathbf{4}^*,\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4}^*,\mathbf{4},\mathbf{1})\\&\quad\oplus(\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4}^*)\oplus(\mathbf{4}^*,\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{4}^*,\mathbf{1},\mathbf{1},\mathbf{4})\oplus(\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{4}^*,\mathbf{1})\oplus[(\mathbf{10}^*,\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\\&\quad\oplus(\mathbf{1},\mathbf{1},\mathbf{10}^*,\mathbf{1},\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{10}^*,\mathbf{1})\oplus(\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},)\oplus(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1})\oplus(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{10})].\end{aligned}$$

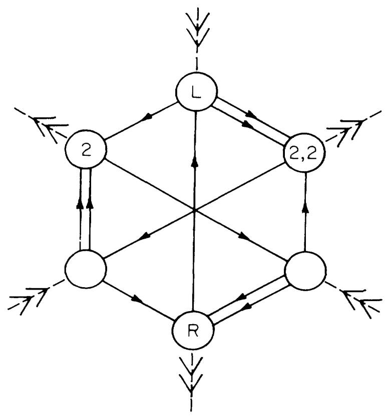

FIG. 1. $[SU(4)]^6$ moose diagram. Solid (dashed) lines denote four- (ten-) dimensional irreducible representations.

The model is most elegantly displayed in moose notation[4] as shown in Fig. 1. The relevant moose resembles a benzene molecule. Cancellation of anomalies is obvious from the moose.

Our chosen fermion representation shows an obvious threefold symmetry. The moose diagram may be rotated by 120° or 240°, or it may be reflected about one of three axes and at the same time conjugated. Thus, our scheme admits the discrete symmetry group S_3 of an equilateral triangle. This symmetry is imposed upon the theory and so there is but one gauge coupling. Our chosen representation, above, consists of five irreducible representations of the extended group. It is, however, a minimal anomaly-free representation in which GIM is natural.

After symmetry breaking to $SU(3)_L \otimes SU(3)_R \otimes SU(2)_L \otimes U(1)$, the fermions in real representations are assumed to become superheavy and precisely the light chiral fermions listed earlier are the survivors.

The unification analysis is similar to that discussed in Ref. 1. Without any scalar bosons, the assumption of a single scale M gives $M = 4 \times 10^9$ GeV and $\sin^2\theta = 0.268$. When scalars are introduced, the fact that many carry chiral color means that the evolution of the couplings is changed significantly: We can assert consistency with the observed $\sin^2\theta$ but cannot estimate either it or M with confidence.

It is encouraging that there exists a model of chiral color which is fully unifiable and with a GIM mechanism equally as natural as in the standard model. We await with interest the outcome of experimental searches for the axigluon to find whether Nature has chosen the chiral-color alternative.

This research was supported in part by the National Science Foundation under Grant No. PHY82-15249, and the U. S. Department of Energy under Grant No. DE-FG-05-85ER-40219.

[a]Permanent address: Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27514.

[1]P. H. Frampton and S. L. Glashow, Phys. Rev. Lett. B [to be published].

[2]S. L. Glashow and S. Weinberg, Phys. Rev. D **15**, 1958 (1977).

[3]A fundamental fermion transforming according to the three-, six-, or eight-dimensional representation of color SU(3) is referred to as a quark, quix, or queight, respectively. The quone is a color-singlet fermion bearing chiral color.

[4]H. Georgi, Nucl. Phys. B **266**, 274 (1986).