Minimal Flavor Unification via Multigenerational Peccei-Quinn Symmetry

Aharon Davidson
International Center for Theoretical Physics, I-34014 Trieste, Italy, and Department of Nuclear Physics,[a]
The Weizmann Institute of Science, Rehovot 76100, Israel

and

Kameshwar C. Wali
Physics Department, Syracuse University, Syracuse, New York 13210
(Received 26 August 1981)

A link between (i) the Peccei-Quinn mechanism, (ii) the canonical fermion mass matrix, and (iii) minimal grand unification is established. The effects of a global versus a local horizontal U(1) symmetry are analyzed. It is pointed out that the weak *CP* nonconservation in such a model has to be accounted for by Higgs exchanges. A possible bridge to composite models is noted.

PACS numbers: 11.30.Er, 12.10.En, 14.60.-z

Recently a very interesting resolution of the strong *CP* problem[1] has been proposed by Dine, Fishler, and Srednicki[2] (DFS). Following an earlier attempt by Kim,[3] DFS have generalized the original Peccei-Quinn (PQ) mechanism[4] to produce an axion whose mass and coupling to normal matter are inversely proportional to an arbitrary vacuum expectation value (VEV) of an SU(2)-singlet complex scalar field. If the VEV is large enough, the DFS axion is invisible, and hence harmless. While such a scenario may be unnatural strictly within the $SU(3)\otimes SU(2)\otimes U(1)$ theory, on the contrary, however, that it is to be expected in a grand unified theory has been pointed out by Wise, Georgi, and Glashow.[5] They have proceeded ahead and constructed a model based on SU(5).

In the present paper we attempt to combine the above ideas with horizontal flavor chirality to construct a multigenerational scheme. Indeed what follows is a model which preserves the grand unification features of a single generation and has, therefore, a single gauge coupling constant. It exhibits a pure nearest-neighbor interaction in the gneration space leading to identical "canonical"[6] structures for the fermion mass matrices. Further the weak *CP* nonconservation is conjectured to be spontaneously generated via the same mechanism which avoids both the strong *CP* nonconservation as well as the axion visibility.

We begin by observing that the basic ingredients of the Peccei-Quinn[4] mechanism are (i) a *global* anomalous axial U(1) symmetry, and (ii) two Higgs doublets. Now a *local* U(1) horizontal symmetry was recently studied[7] in some detail to understand the implications of horizontal flavor chirality on the fermion mass matrix m_F. Such a U(1) symmetry in the generation space has to be necessarily axial if the generation structure is taken to be pure, e.g., SO(10) embeddable. It is primarily this axial nature which constrains the fermion mass matrix and determines its general structure and its phase contents. The locality through the anomaly-free conditions correlates the fermion mass matrices in the two charge sectors. These considerations along with the requirement of nondegeneracy in the horizontal assignments and nondegenerate eigenmasses led us to conclude that (i) at least two scalar doublets are necessary, and (ii) m_F acquires uniquely a Fritzsch-type[6] canonical structure.

The axial nature of the extra U(1) along with the obvious need for two Higgs doublets suggests a connection between the proposed solution of the strong *CP* problem and the generation puzzle. Furthermore, the use of global symmetries in classifying fermionic families allows us to maintain the spirit of a single gauge coupling constant in the minimal possible way. After all, the question, why have unification at the single-generation level, has been with us for quite a long time. We thus propose a grand unifying scheme based on $G\otimes U(1)_{PQ}$, with $G=SU(5)$ or SO(10) and with $U(1)_{PQ}$ playing the role of a generalized horizontal symmetry. This is fully consistent with our basic point of view, as stated in our study of vertical $\leftrightarrow$ horizontal symmetric theories,[8] namely that the single-generation group factor is elementary and not a consequence of some symmetry-breaking process.

Let the left-handed spin-$\frac{1}{2}$ chiral fields $\psi_L{}^i$ associated with the ith generation transform under $U(1)_{PQ}$ as follows:

$$\psi_L{}^i \to \exp(iax_i)\psi_L{}^i. \quad (1)$$

It is now important to note that the presence of a global U(1) at the level of the classical Lagrangian implies an *axial* $U(1)_A$ for a "pure" generation structure. For, if f_L and $f_L{}^c$ are members of the same irreducible multiplet, f_L and f_R must carry opposite horizontal assignments. This is how the PQ symmetry and flavor chirality come together. Vertical SO(10) unification ties all family members, forcing them to carry the same PQ assignments. For simplicity, however, we choose to make our point using $G = SU(5)$, but imposing common x_i on both $\psi_{10}{}^i$ as well as $\psi_{5^*}{}^i$. The scalar sector consists of two Weinberg-Salam doublets [$\underline{5}$ and/or $\underline{45}$ in SU(5) language] φ and φ', to which the DFS scalar Φ is added. Under $U(1)_{PQ}$ they transform as

$$\varphi \to e^{iah}\varphi, \quad \varphi' \to e^{iah'}\varphi', \quad \Phi \to e^{iaH}\Phi. \quad (2)$$

We have the option to interpret Φ as either $\underline{24}$ *à la* Wise, Georgi, and Glashow,[5] or as an $\overline{SU}(5)$ complex singlet if an intermediate mass scale is found necessary. At any rate, the horizontal quantum numbers must satisfy

$$x_i \neq x_j \text{ for } i \neq j, \; h \neq h', \quad (3)$$

as otherwise the flavor problem would be still unsolved.

To study the structure of m_F, it is convenient to use the matrix X defined by $X_{ij} = x_i + x_j$. Consider, for example, the down-quark sector and those elements of X which equal h or h'. They signify nonvanishing Yukawa couplings, and therefore correspond to nonvanishing $m(d)$ matrix elements which are proportional to $\langle\varphi\rangle = ve^{i\alpha}$ or $\langle\varphi'\rangle = we^{i\beta}$, respectively. The procedure, however, is severely restricted by (3) and by the demand of having no zero eigenmasses. Moreover, we can use our experience from the local $U(1)_A$ model[7] to infer that X is fixed *uniquely* (that is up to permutations) for any arbitrary number N of generations. It has been shown that

$$X_{kk} = h\delta_{kN}, \quad X_{kk-1} = \begin{cases} h \text{ for } N-k \text{ odd}, \\ h' \text{ for } N-k \text{ even}. \end{cases} \quad (4)$$

From (4), in the case of $N = 3$, for example,

$$x_1 = \tfrac{3}{2}h - h', \quad x_2 = h' - \tfrac{1}{2}h, \quad x_3 = \tfrac{1}{2}h, \quad (5)$$

and the matrix X is given by

$$X = \begin{pmatrix} 3h - 2h' & h & 2h - h' \\ h & 2h' - h & h' \\ 2h - h' & h' & h \end{pmatrix}. \quad (6)$$

The fermionic PQ assignments are thus fully dictated by the Higgs system of the theory.

Now we notice that if $x_i + x_j = h$ or h' is the criterion for determining the allowed Yukawa couplings and hence the nonvanishing terms in $m(d)$, it is $x_i + x_j = -h$ or $-h'$ which determines the nonvanishing terms in $m(u)$, the up-quark mass matrix. Further, since the form of X is fixed in terms of h and h', it contains the relevant information for construction of $m(u)$. However, it is at this stage *where the global versus local nature of the axial U(1) acquires importance.* Locality implies $h = 0$ because of the anomaly cancellation conditions, $\sum x_i = \sum x_i{}^3 = 0$, leading to a relative deformation in the structure of $m(u)$ in comparison with the structure of $m(d)$. This deformation is easily seen by comparing the locations of h vs $-h$ terms in X. Globality, on the other hand, requires $h \neq 0$ in order to allow color anomalies ($\sum x_i \neq 0$) to remove nonperturbatively the axion masslessness. Furthermore, the only way to assure no tree-level massless up quarks, without loosing color anomalies, is to require

$$h + h' = 0. \quad (7)$$

Notice the naturalness of this relation for $G = SO(10)$. For example, $\underline{10}$ of SO(10) decomposes into $\underline{5} \oplus \underline{5}^*$ under SU(5), so that the two $\underline{5}$'s automatically carry *opposite* PQ assignments. What Eq. (6) actually tells us is that, up to an overall scale, only one set of x_i's, namely $\tfrac{1}{2}h$, $-\tfrac{3}{2}h$, $\tfrac{5}{2}h, \ldots$, is consistent with all the requirements.

The fermion mass matrices are now uniquely fixed (up to Yukawa couplings) and are one-to-one correlated:

$$m(d) = \begin{pmatrix} 0 & d_1 ve^{i\alpha} & 0 \\ d_2 ve^{i\alpha} & 0 & d_3 we^{i\beta} \\ 0 & d_4 we^{i\beta} & d_5 ve^{i\alpha} \end{pmatrix}, \quad (8a)$$

$$m(u) = \begin{pmatrix} 0 & u_1 we^{-i\beta} & 0 \\ u_2 ve^{-i\beta} & 0 & u_3 ve^{-i\alpha} \\ 0 & u_4 ve^{-i\alpha} & u_5 we^{-i\beta} \end{pmatrix}, \quad (8b)$$

where $d_1, d_2, \ldots, d_5$ and $u_1, u_2, \ldots, u_5$ are arbitrary Yukawa couplings. The following comments and clarifications summarize their important features:

(1) In the above mass matrices, we have assumed that two "light" Higgs doublets survive when the symmetry is broken down to SU(3) $\otimes$ SU(2)$\otimes$ U(1). This is because we want to obtain a realistic quark mass spectrum. Previously, using the $U(1)_A$ local symmetry,[7] we have shown that a minimum of two Higgs doublets are necessary in order to have nondegenerate, nonzero eigenvalues for the masses. The same situation prevails here as well, where we are using $U(1)_{PQ}$ global symmetry to restrict the mass matrices. In the single-generation Wise-Georgi-Glashow[5] version of the DFS scheme, there is only one light Higgs doublet with one "unnatural" constraint. Following the philosophy of Ref. 5, we let the fundamental hierarchy problem remain. In order to obtain an additional light Higgs doublet within the framework of a grand unified scheme, we will have to impose an additional "unnatural" constraint.

(2) If we assume that the mass matrices (8a) and (8b) are symmetric, their diagonalization leads to mixing angles which are expressible in terms of the quark mass ratios. The Cabibbo angle is given by $\theta_c \simeq (m_d/m_s)^{1/2}$. The symmetry implies that the Yukawa couplings be symmetric. This can be accomplished, for example, choosing representations $\underline{10}, \underline{126}$ for the Higgs multiplets in the grand unified theory based on SO(10).

(3) The original PQ feature regarding u and d quarks acquiring their masses via different VEV's is maintained for each m_{ij} separately. If $m(d)_{ij} \sim v, w$, then $m(u)_{ij} \sim w, v$, and vice versa. This, however, is not sufficient to ensure natural flavor conservation in the Higgs sector. There will be flavor-changing neutral currents in the model. These, however, will be correlated with the strength and phases of the weak CP nonconservation.

(4) With real Yukawa couplings, the diagonalization of $m(u)$ and $m(d)$ leads to a *real and orthogonal* Cabibbo matrix U_c. This means that there is no Kobayashi-Maskawa[9] (KM) phase and hence *no CP nonconservation in the gauge interactions.*

The elimination of the weak CP nonconservation from KM formalism is an attractive feature of $U(1)_A$ horizontal symmetries. It gives rise to the possibility that one might account in a natural way for the small magnitude of the CP-nonconservation effect and hopefully also for its superweak character. We have shown[7] how a local $U(1)_A$ relegates the CP-nonconservation effect along with flavor-changing neutral currents to the exchange of a single vector gauge boson. In the case of the global $U(1)_{PQ}$ symmetry, CP nonconservation and flavor-changing neutral currents are entirely due to Higgs exchanges which mediate the $\Delta s = 2$ bare transitions

$$\bar{d}_L{}^i \bar{d}_L{}^j \to d_R{}^j \bar{d}_R{}^i \quad \text{and} \quad d_L{}^i \bar{d}_R{}^j \to d_L{}^j \bar{d}_R{}^i. \tag{9}$$

Our preliminary investigation shows that a realistic and satisfactory model within the framework of an SO(10) grand unification scheme can be constructed, using $\underline{10}$ and $\underline{126}$ representations for the Higgs multiplets that couple to the fermions. There is some arbitrariness regarding the representations that do not couple to the fermions, but that can be used in the Higgs potential subject to $U(1)_{PQ}$ symmetry. This question has to be decided by a detailed quantitative investigation of the CP-nonconservation effects, flavor-changing neutral currents, and other relevant considerations.

It is also worth observing that the type of grand unification that emerges from these ideas is different from that of 't Hooft.[10] First of all, a $U(1)_{PQ}$ symmetry is imposed on the theory. The discrete unique horizontal assignments ($x_i = \frac{1}{2}h$, $-\frac{3}{2}h$, $\frac{5}{2}h$, $-\frac{1}{2}h, \ldots$) that arise indicate a symmetry under some discrete subgroup of $U(1)_{PQ}$—a situation somewhat like that in the Harari-Seiberg dynamical Rishon model,[11] where a discrete Z_{12} subgroup of some global axial U(1) survives the symmetry-breaking process. The assignments also suggest an underlying substructure. Since they are such that the assignments for the Nth generation remain unaffected when we go from N to $N+1$ generations, we may visualize a theory in which there is only one elementary fermionic family, all others being composites of this fermionic family with the Higgs scalars. These and other related problems are currently under study.

One of us (A.D.) would like to thank Professor A. Salam for his hospitality at the International Center for Theoretical Physics, Trieste, and for his interest and encouragement. He would also like to acknowledge critical discussions with Professor J. C. Pati, Professor E. Witten, Professor R. Barbieri, Professor J. E. Kim, and Professor S. Rajpoot. K. C. W. would like to thank Professor H. H. Tye, Professor J. Schechter, Professor H. Georgi, and Professor Helen Quinn for helpful discussions. He would also like to thank V. P. Nair for his help in the verification of some ideas contained in the paper.

[a]Permanent address.
[1]C. G. Callan, R. F. Dashen, and D. J. Gross, Phys. Lett. 63B, 334 (1976); R. Jackiw and C. Rebbi, Phys. Rev. Lett. 37, 172 (1976).
[2]M. Dine, W. Fishler and M. Srednicki, Phys. Lett. 104B, 199 (1981).
[3]J. Kim, Phys. Rev. Lett. 43, 103 (1979).
[4]R. Peccei and H. Quinn, Phys. Rev. Lett. 38, 1440 (1979).
[5]M. B. Wise, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 47, 402 (1981).
[6]H. Fritzsch, Phys. Lett. 70B, 436 (1977), and Nucl. Phys. B155, 189 (1979).
[7]A. Davidson and K. C. Wali, Phys. Rev. Lett. 46, 691 (1981), and to be published.
[8]A. Davidson, Phys. Lett. 90B, 87 (1980), and 93B, 183 (1980); A. Davidson, P. D. Mannheim, and K. C. Wali, Phys. Rev. Lett. 45, 1135 (1980).
[9]M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 642 (1973).
[10]G. 't Hooft, Lecture given at the Cargese Summer Institute (1979).
[11]H. Harari and N. Seiberg, Phys. Lett. 98B, 269 (1981), and 102B, 263 (1981).

Diquark Deuteron

Sverker Fredriksson and Magnus Jändel
Department of Theoretical Physics, Royal Institute of Technology, S-100 44 Stockholm 70, Sweden
(Received 9 October 1981)

It is speculated that an almost stable state of hadronic and nuclear matter can be built from *diquarks*. It is suggested that this alternative form of matter has already revealed itself in existing experimental data in the form of a diquark "deuteron" with $J^P = 0^-$ and with several other anomalous properties.

PACS numbers: 12.35.Ht, 14.20.Pt

The aim of this Letter is to present evidence for the existence of a deuteronlike object consisting of *three diquarks*. Because of lack of space we will present elsewhere a much more detailed analysis of all aspects of our predictions. Here we limit ourselves to discussing some of the most important properties of such an object as well as some of the experimental support for our theoretical ideas.

In a recent experiment at the Lawrence Berkeley Laboratory indications were found[1] that nuclear matter can exist in a form with strange properties. Earlier the same effect had been observed in cosmic-ray experiments.[2] When a high-energy nucleus collides with an emulsion target, around 6% of the projectile fragments stop in the emulsion much faster than is considered normal for heavy ions. This finding suggests that those fragments contain some hitherto unexplored phase of nuclear matter ("anomalons"), with a very high reaction cross section and a long lifetime (10^{-10} to 10^{-9} s)—definitely stable against strong decays.

In order to simplify the analysis of this astonishing phenomenon we have investigated *deuteronlike* objects in search of anomalous states.

Among all possible combinations of the six quarks of a two-nucleon object we have found that a system of three diquarks has some unique properties that make it a strong candidate for a light anomalon. Preliminary speculations about this "demon deuteron" have been reported by us at two conferences.[3,4] In the following we will use the word "demon" and the symbol δ for the diquark deuteron, saving "anomalons" for the observed fragments.

It is fairly obvious that a three-cluster arrangement is needed, since any other structure gives a mass which exceeds the threshold, 2.013 GeV/c^2, for a strong decay to an $NN\pi$ system.[5,6] Our particular choice of diquark configuration, as discussed below, is guided by physical reasoning and symmetry principles.

The contribution of the color-magnetic interaction to the mass of an N-quark cluster is proportional to[7]

$$\Delta = -\tfrac{1}{3}N(6-N) + \tfrac{1}{3}\bar{J}^2 + \bar{I}^2 + \tfrac{1}{2}F^2. \tag{1}$$

F^2 is the squared Casimir operator of $SU(3)_{\text{color}}$, and J and I are the cluster total angular momentum and isospin, respectively. It is hence energetically favorable to couple the constituents of a diquark into the representations $\underline{3}^*$ of color and singlets of both spin and isospin. Each diquark therefore has $(I, S, J^P)_{\text{diquark}} = (0, 0, 0^+)$.

Having all three diquarks in S orbitals would

