Chiral aspon model: An alternative fully gauged model of *CP* violation

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A chiral aspon model is constructed which avoids problems with quantum gravity violation of continuous global symmetries. The model contains only gauged local symmetries before spontaneous symmetry breaking, has no vectorlike fermions with bare mass terms, solves strong *CP* conservation, and has calculable weak *CP* violation. The model requires axigluons with mass locked to the aspon scale.

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Symmetry principles play a deep role in our understanding of elementary particle interactions. Gauge symmetries underly the theories of strong and electroweak interactions. Behavior with respect to discrete global symmetries such as parity (*P*), charge conjugation (*C*) and time reversal (*T*) is central to the formulation of phenomenologically successful quantum field theories. Particularly in the development of weak interaction theory, these discrete symmetries have played the dominant role. There are very general arguments that suggest the product (*PCT*) is an exact symmetry but it has been known for almost three decades that the separate factors (*CP*), or equivalently *T*, are not exact, only approximate symmetries of the weak interaction [1]. Not only is *CP* an inexact symmetry of the weak interaction (where it is broken at the 0.2% level) but it is a concern also for strong interactions because of the so-called strong *CP* problem [2].

Previously there have been a number of possible solutions to the strong *CP* problem none of which is fully satisfactory. The simplest solution is to set the mass of the up quark to zero [3] but this is inconsistent with spontaneous breaking of chiral symmetry and the pseudoscalar-meson mass spectrum. A second solution is to impose the Peccei-Quinn symmetry which leads to axion physics [2,3] but the axion remains experimentally elusive with the allowed mass region becoming more and more constrained, and recently the compatibility of global U(1) symmetries with quantum gravity has been called into question [4]. A third solution which avoids such global U(1) symmetries is the technique [5,6] in grand unified theories with spontaneous *CP* violation [7]. Fourthly, there is the aspon model [8–11] which has some successes including a simulataneous fit to weak and strong *CP* which is testable at the Superconducting Super Collider (SSC) and has no global symmetry except *CP* itself [12], but the one drawback of the original aspon model is that there are vectorlike quarks with masses which are unprotected by any symmetry.

As a dramatic improvement in the aspon model we now discuss a method of avoiding the one unpleasant feature of the model, viz., the nonchiral heavy-quark coupling to the aspon. By a modification of the gauge group we shall restore to the theory its full chirality which is a hallmark of the successes of the standard model. The present model is thus an example in which (i) *CP* is broken spontaneously at the TeV scale, (ii) the early cosmology is viable by invoking late-time inflation and weak-scale baryogenesis, (iii) there must be testable consequences at SSC energies, (iv) there is a new mechanism, beyond the Cabibbo-Kobayshi-Maskawa (CKM) phase, of weak *CP* violation, and (v) once the *CP* violation scale is introduced, no further fine-tuning is required beyond that of the standard model.

We adopt the chiral-color gauge group [13]

$$SU(3)_{CL}\times SU(3)_{CR}\times SU(2)_L\times U(1)_Y\times U(1)_{\rm new}$$

and adopt fermions:

$$3\left[\left(3,1,2;\frac{1}{3}0\right)+\left(1,\bar{3},1;\frac{2}{3},0\right)+\left(1,\bar{3},1;\frac{-4}{3},0\right)+(1,1,2;-1,0)+(1,1,1;+2,0)\right]$$
$$+\left(3,1,1;\frac{4}{3},+5\right)+\left(1,\bar{3},1;\frac{-4}{3},-5\right)+\left(\bar{6},1,1;-\frac{2}{3},-1\right)+\left(1,6,1;+\frac{2}{3},+1\right). \quad (1)$$

Cancellation of anomalies dictates that we introduce an additional quark U with charge $+\frac{2}{3}$. But this heavy quark is *not* vectorlike by virtue of chiral-color symmetry which is assumed to be broken at the scale of spontaneous *CP* violation.

The Higgs scalars needed to break the symmetries are

$$\chi^{\alpha}(\bar{3},3,1;0,-5)\quad(\alpha=1,2)\ , \quad (2a)$$

$$S(6,\bar{6},1;0,0)\ , \quad (2b)$$

$$\phi(\bar{3},3,2;\pm 1,0)\ , \tag{2c}$$

$$\phi'(1,1,2;+1,0)\ . \tag{2d}$$

The vacuum values (VEV's) of the first two break $U(1)_{\text{new}}$ and chiral color (at a common scale) and give mass to the axigluon and the quix. The ϕ and ϕ' play the role of the conventional Higgs doublet of the standard model.

Finally we shall need a scalar $H(3,1,2;-1,+5)$ which has no VEV but can couple the U to light quarks. This allows the U to contribute to weak CP violation at a scale comparable to that of the $Q=(U,D)$ doublet in Ref. [8], and makes the present model at least equally as viable phenomenologically as well as having the theoretical improvements already indicated.

The axigluon mass scale is linked through the χ coupling to the aspon scale and thus we expect the axigluon to be ≤ 600 GeV—heavier than antipaciated in the original paper [13] which assumed a linkage between the axigluon scale and the weak scale.

Observe that after chiral color breaking the U color-triplet fermions (quirks) become vectorlike and develop a mass at the axigluon-aspon scale:

$$U=(3,1)_{2/3};\quad \bar{U}=(\bar{3},1)_{-2/3}\ , \tag{3}$$

where the subscript is electric charge. These are to be compared with the vectorlike quirks of the original aspon model [8]:

$$(3,2)_{1/3},\quad (\bar{3},2)_{-1/3}\ . \tag{4}$$

This model would also be viable with a singlet vectorlike D quark or (with a modified Higgs sector) with a singlet vectorlike U quark.

Chiral color [13] was originally motivated only by the analogy between the strong and electroweak sectors but here it is an essential part of the model to ensure all fermions acquire mass only *after* symmetry breaking. We may say that chiral color and the aspon mechanism have a symbiotic or even a heterotic relationship.

With the fermions arranged as in (1) above, the triangle anomalies $(3_{CL})^3$, $(3_{CR})^3$, $(3_{CL})^2Y$, $(3_{CL})^2A$, $(3_{CR})^2Y$, $(3_{CR})^2A$, $(2_L)^2Y$, $(2_L)^2A$, Y^3, Y^2A, YA^2, and A_3 can all be shown to vanish. Here the notation is self-explanatory except that A for aspon is the $U(1)_{\text{new}}$ charge. The $(3_{CL})^2Y$, $(3_{CR})^2Y$ anomalies force the additional quark to have electric charge $+\frac{2}{3}$ (like an up quark) if we insist

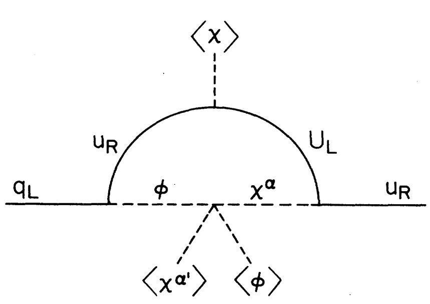

FIG. 1. One-loop contribution to $\bar{\theta}$.

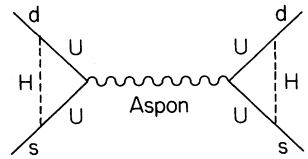

FIG. 2. Weak CP violation by aspon exchange.

that the quix have electric charge which is an integer multiple of $(\frac{1}{3})$. The fermions in (1) are the minimal set which is chiral under the given gauge group and which cancels all anomalies.

Let us denote the light quarks by q_L^i, $\bar{u}_L^i$, $\bar{d}_L^i$ $(1\leq i\leq 3)$ where $q\equiv(u,d)$. Then the Higgs scalars χ^α couple the U_L $(3,1,1;\frac{4}{3},+5)$ to the $\bar{u}_L^i$ and give an up-quark mass matrix of the form

$$M_{\text{up}}=\begin{bmatrix} M_u & O \\ \underline{F} & M \end{bmatrix}\ , \tag{5}$$

with $\underline{F}=\underline{h}^1\langle\chi_1\rangle\underline{h}^2\langle\chi_2\rangle$ complex, and the 3×3 M_u, and M, real by assumption of CP conservation [14]. The down-quark mass matrix is real 3×3.

By a parallel argument to Ref. [9] the flavor-changing neutral currents (FCNC's) are smaller than in the standard model [15].

The one-loop contributions to $\bar{\theta}$ were considered in Ref. [9] and only one diagram [Fig. 4(g) therein] was found to contribute. Similarly in the present model only one diagram contributes, viz., Fig. 1, for which the estimate of the upper limit of the Yukawa couplings of the Higgs scalar χ follows that of Refs. [9–11].

The aspon-exchange diagram contributing to CP violation is given by Fig. 2. The estimate of the present model modifies that of the original aspon model by a factor $(x_i=F_i/M)$

$$\left[\frac{h^2}{16\pi^2}\right]\frac{1}{(x_1x_2)^2}\approx h^4 10^{-4}$$

so that for $h\approx 0.1$, the weak CP violation is comparable to the successful estimate of Ref. [9]. Thus the CP violation phenomenology is no problem.

Of particular interest is that the chiral color scale is locked to the aspon scale and that thence the axigluon mass is now naturally at or below 600 GeV and hence visible at SSC.

In summary, we have constructed a chiral gauged model incorporating strong CP conservation and weak CP phenomenology. The model avoids all the pitfalls encountered previously such as the criticisms of global symmetries. It improves on the previous aspon model by avoiding vectorlike quarks with unprotected bare mass terms. Finally, the model can be tested at the SSC by searching for the aspon and the axigluon which have comparable masses expected to be below 600 GeV.

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[14] Note that Eq. (5) of the text differs from Eq. (14) of Ref. [9]. This difference in the position of the zeros is why additional quarks of the aspon model must be either all SU(2) doublets or all SU(2) singlets in order to solve strong *CP*.
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