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A Preon Model with Minimal Color-Flavor Number and Low Composite Energy Scale

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Abstract

A preon model with minimal color-flavor number and low composite energy scale is proposed. Three generations of massless quarks and leptons (but no exotic fermions) can be reproduced by assuming the global chiral symmetry SU(10) of the preon Lagrangian to be spontaneously and maximally broken down to unbroken chiral subgroup $SU(3)_L X\ SU(3)_R X\ SU(2)_L X\ U(1)_Y$ which minimally contains the gauge group $SU(3)_C X\ SU(2)_L X\ U(1)_Y$ of the standard model as a subgroup. The 't Hooft anomaly matching condition naturally leads to the generation structure of quarks and leptons. A constraint from coupling of this theory to gravity is also considered.

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§ 1 Introduction

Motivated by a proliferation of quarks and leptons and the apparent arbitrariness of their masses, some theorists have speculated that quarks and leptons may not be elementary but rather composed of some "preons" (1). Especially, it was suggested that the color and flavor of a quark or a lepton may eventually come from the color and flavor of constituent preons, and each one of preons carries only one of these quantum numbers and has only one function(2). By this way that one preon carries only one color or one flavor the origin of colors and flavors of quarks and leptons could be explained to some extent and it is essentially one of the most important motivations of the preon models. However, most of the models along this direction were based on simple quantum number counting and did not contain any preon dynamics. Particularly, they did not give any answer to another basic problem of preon models that the Compton wavelenth of quarks and leptons is much larger than the upper limit of their size(3).

By adopting the 't Hooft's suggestion that unbroken chiral symmetries of the fundamental Lagrangian of the preon system may be responsible(4), a large classification of possible metacolor group and metacolor representations (preons) have been found (5) that yield a predetermined set of massless composite states. However, for these models to describe nature the preons have been assigned to have exactly the same color-flavor quantum numbers as those of one generation of quarks and leptons (5)-(7). Thus these models have no explanation for the origin of the color-flavor quantum numbers.

In a very recent paper (8), Marshak and the present author have proposed a program towards a realistic composite model of quarks and leptons. The program has certain attractive features. Firstly, it can reproduce at least the observed three generations of quarks and leptons without exotic fermions by assuming that the global chiral symmetry group G_{CF} of the preon Lagrangian (9) is spontaneously and maximally broken down to an unbroken chiral subgroup H_{CF} which minimally contains a " low energy " color-flavor gauge group as a subgroup, and using the 't Hooft anomaly matching condition. Secondarily, the number of color-flavors of preons could be less than those of one generation of quarks and leptons. Thus it gives some explanation for the origin of color-flavors. In other words, this program in essence solves these two problems of preon models simutaneously.

In this paper we would like to follow the same program and to present a preon model with minimal color-flavor number and low composite energy scale. The paper is organized as follows. In section 2 the color-flavor quantum numbers of preons are determined by coupling them to the gauge group of the standard model $SU(3)_C\times SU(2)_L\times U(1)_Y$ and gravity. It is shown that correct quantum number counting, the vector-like electric charge and color charges and anomaly free conditions uniquely fix the model. In section 3, the solutions to the 't Hooft anomaly matching conditions are explored by assuming that the global chiral symmetry group SU(10) is spontaneously and maximally broken down to unbroken chiral subgroup $SU(3)_L\times SU(3)_R\times SU(2)_L\times U(1)_Y$ which minimally contains the gauge group $SU(3)_C\times SU(2)_L\times U(1)_Y$ as a subgroup. It is shown that the index solution to the 't Hooft anomaly matching conditions with massless quarks and leptons and without exotic fermions can be found although the conditions are more restrictive. The number of families is directly related to the dimension of the metacolor representation of preons which carry non-trivial color-flavor quantum numbers. Finally, in section 4 we give some concluding remarks.

§ 2 A $SU(3)_C$X $SU(2)_L$X $U(1)_Y$ preon theory

A program towards a realistic composite model of quarks and leptons has been described in detail in the reference (8). In this paper, we shall identify the gauge group of the standard model [10] as the gauge part g_{CF} of the global chiral symmetries G_{CF} of the preon Lagrangian, that is

$$g_{CF} = SU(3)_C\times SU(2)_L\times U(1)_Y \qquad (1)$$

This identification may be the only relevent one if it turns out in future experiments that the composite energy is relative low, for example, around hundreds Tev region. This is because the energy scale for g_{CF} to be unbroken in general should be lower than the composite energy scale if the composite energy scale is not vastly different from the chiral symmetry breaking energy scale, as we have discussed in reference (8).

As the first step of the program suggested in reference (8), a $SU(3)_C$ X $SU(2)_L\times U(1)_Y$ preon theory should be constructed out such that it is free of color-flavor anomaly and gravitation anomaly [11], and has the vector-like electric charge and color charges. This can be realized in a very naive way by assuming that the preons have exactly the same color-flavor quantum numbers as those of one generation of quarks and leptons. However, we would like in

this paper to look for the model in which number of color-flavors can be reduced in order to give some explanation to the origin of the color-flavor quantum numbers. As we have discussed, this can be done if we let one left-handed preon carry just one color or one flavor [2]. In the case that g_{CF} is identified as the low energy color-flavor gauge group $SU(3)_C\times SU(2)_L\times U(1)_Y$, it turns out that the minimal number of color-flavors of preons is ten and the preon contents are

$$(3,1)_a+(\bar{3},1)_b+(1,2)_c+(1,1)_d+(1,1)_e \qquad (2)$$

where $(\alpha,\beta)_i$ stands for the representation α,β of the group $SU(3)_C$ and $SU(2)_L$ respectively, and i is $U(1)_Y$ quantum number.

The first constraint on $U(1)_Y$ quantum number comes from the anomaly free conditions for $SU(3)_C\times SU(2)_L\times U(1)_Y$

$$1 - 1 = 0 \qquad (3)$$

$$a + b = 0 \qquad (4)$$

$$c = 0 \qquad (5)$$

$$3(a^3+b^3)+2c^3+(d^3+e^3)=0 \qquad (6)$$

In addition, the $SU(2)_L\times U(1)_Y$ theory cannot be coupled to gravity unless the sum of the hypercharges of the left-handed preons vanishes [11], namely

$$3(a+b)+2c+(d+e)=0 \qquad (7)$$

From eqs. (3)-(7) we have

$$a=-b$$

$$d=-e$$

$$c=0 \qquad (8)$$

Free of gravitation anomaly condition, eq. (7), plays an important role in determing the solution eq. (8) uniquely.

The exact values of these numbers depend on models. Particularly, they depend on the compositions of quarks and leptons as composite fermions. In the model we shall discuss, quarks and leptons are assumed to be composed of three fermionic preons, and only two of them carry color or flavor, another constituent preon which is color-flavor singlet carries the spin only in accordance to the spin 1/2 of composites. The composite fermions with such a structure can be easily worked out in chiral preon models [9], as we have shown in the reference (8). In the most simple case, the binding force between these preons can be assumed as the SU(N) meta-color interaction. The preons which carry the color-flavor quantum numbers are put in the fundamental representation of the SU(N) meta-color group while the color-flavor singlet preon can be assigned into the rank two symmetric or anti-symmetric representation [12]. The composite fermion in this case are meta-color singlet of three preons. The meta-color properties and the global chiral symmetries G_{CF} of preon Lagrangian are summarized in the Table 1.

Obviously, the preon theory should reproduce the observed quarks and leptons at composite level when the meta-color binding force turns on. By taking the composition of quarks and leptons into account and after simple quantum number counting we find

$$\begin{aligned} a &= 1/3 \\ b &= -1/3 \\ c &= 0 \\ d &= 1 \\ e &= -1 \end{aligned} \tag{9}$$

The color-flavor quantum numbers of preons are summarized in Table 2, where all preons are assumed as left-handed only for simplicity.

We should point out the connection with the spinor-subquark model suggested by Terazawa, Chikashige and Akama some years ago [13]. In the spinor-subquark model the subquarks which carry the weak-isospin, horizontal and color quantum numbers are called as " wakems ", " hakams " and " chroms " respectively. All of them have their own anti-particles. As the result, the electroweak interaction in this model is left-right symmetric [14]. Whereas in our model there is only one left-handed doublet " wakems ", the electroweak interaction is therefore left-handed only.

More important differences come from the dynamics. The original spinor-subquark model was essentially based on the simple quantum number counting, and very few about subquark dynamics was involved. One possible candidate for binding force between subquarks was suggested as the QCD-like

subcolor force [13]. However, as it has been shown [9], the QCD-like force in general leads to a spontaneously broken chiral symmetry. It is therefore necessary to introduce some mechanism other than the exact unbroken chiral symmetry to explain why the mass of composite quarks and leptons can be so smaller than the binding energy scale of subcolor force. Furthermore, the spinor-subquark model also did not answer the exotic fermion problem, namely why is there no exotic fermion which is not made of one wakem, one hakam and one chrom ? On the other hand, these two problems, massless composites and no exotic fermion, can be solved in our model if working on the program suggested in reference (8).

§ 3 't Hooft anomaly matching condition and no exotic solution

The basic strategy of the program is to assume that the global chiral symmetry group G_{CF} of the preon Lagrangian is spontaneously and maximally broken down to an unbroken chiral subgroup H_{CF} which minimally contains a " low energy " color-flavor gauge subgroup. The 't Hooft anomaly matching conditions then can be used to find a solution with massless quarks and leptons but no exotic fermions. In this program, the generation quantum numbers are not carried by the constituent subquarks " hakams ". Instead, the number of generations (families) is directly related to the 't Hooft indices. Specifically, for the present case

$$\begin{aligned} G_{CF} &= SU(10) \\ H_{CF} &= SU(3)_L \times SU(3)_R \times SU(2)_L \times U(1)_Y \\ g_{CF} &= SU(3)_C \times SU(2)_L \times U(1)_Y \end{aligned} \tag{10}$$

All possible meta-color singlet composites of three spin 1/2 preons are given in Table 3 with the corresponding 't Hooft indices. By counting the quantum numbers of the composite fermions it is easy to find that after gauging $SU(3)_C \times SU(2)_L \times U(1)_Y$ all composite fermions associated with the m-type indices are exotic fermions while a composite fermion associated with the l-type or s-type index can be identified either as a quark-lepton or as a mirror fermion depending on sign of the l-type or s-type index.

The 't Hooft anomaly matching conditions for $H_{CF} = SU(3)_L \times SU(3)_R \times SU(2)_L \times U(1)_Y$ can be written as

$$- l_3' + 7\, m_1 + 3\, m_5 + 2\, l_1 + s_4 + s_3 = D(R) \tag{11}$$

$$- s_3' + 7\, m_2 + 3\, m_5 + 2\, s_1 + l_3 + l_4 = D(R) \tag{12}$$

$$l_3' + 5\, m_1 + l_1 + 2\, s_4 - s_3 = D(R)/2 \tag{13}$$

$$s_3' + 5\, m_2 + s_1 + 2\, l_4 - l_3 = D(R)/2 \tag{14}$$

$$(l_1 - s_1) + (s_2 - l_2) = 0 \tag{15}$$

$$4\, (l_3 - s_3 + l_3' - s_3') + 8\, (m_1 - m_2) + 36\, (l_5 - s_5) + (l_1 - s_1) + 32\, (s_4 - l_4) + 9\, (s_2 - l_2) = 0 \tag{16}$$

where D(R) is the dimension of the metacolor representation of the preon which carries non-trivial color-flavor quantum numbers.

One more equation must be added to the above equations if the $SU(2)_L \times U(1)_Y$ theory is coupled to gravity [11]

$$(l_1 - s_1) - (l_2 - s_2) + (l_3 - s_3 + l_3' - s_3') - 2(l_4 - s_4) + (l_5 - s_5) + 2\, (m_1 - m_2) = 0 \tag{17}$$

The 't Hooft anomaly matching conditions do put more constraints on the model construction in this case as is expected. However, our purpose is looking for the solution with no exotics and this implies that

a) All m-type indices have to be taken as zero

$$m_i = 0 \qquad (\text{for all } i) \tag{18}$$

and b) All l-type indices should be positive integers and all s-type indices should be negative integers

$$l_i > 0 \tag{19}$$

$$s_i \leq 0 \tag{20}$$

Substituting eq. (18) into eqs. (11)--(17), we obtain

$$2\Delta_1 - (\Delta_3 + \Delta_3') - \Delta_4 = 0 \tag{21}$$

$$\Delta_1 + (\Delta_3 + \Delta_3') - 2\Delta_4 = 0 \tag{22}$$

$$\Delta_1 - \Delta_2 = 0 \tag{23}$$

$$\Delta_1 - 9\Delta_2 + 4\, (\Delta_3 + \Delta_3') - 32\Delta_4 + 36\Delta_5 = 0 \tag{24}$$

$$\Delta_1 - \Delta_2 + (\Delta_3 + \Delta_3') - 2\Delta_4 + \Delta_5 = 0 \tag{25}$$

$$2\Sigma_1 + (\Sigma_3 - \Sigma_3') + \Sigma_4 = 2\, D(R) \tag{26}$$

$$\Sigma_1 - (\Sigma_3 - \Sigma_3') + 2\Sigma_4 = D(R) \tag{27}$$

where we have introduced the Σ-type and Δ-type indices

$$\Sigma_i = l_i + s_i \tag{28}$$

$$\Delta_i = l_i - s_i \tag{29}$$

The Δ-type indices have direct physical meaning. Particularly, the $\Delta_1, \Delta_2, \Delta_3 + \Delta_3', \Delta_4$ and Δ_5 are the number of left-handed multiplet $(u, d)_L$, $(\nu, e)_L$, d_R^c, u_R^c and e_R^c respectively. From eqs. (21)--(25) we find that

$$\Delta_1 = \Delta_2 = \Delta_3 + \Delta_3' = \Delta_4 = \Delta_5 = K \tag{30}$$

The 't Hooft anomaly matching conditions in this case automatically lead to the generation structure of quarks and leptons. Therefore K is the number of families. Again the anomaly matching condition for gravitation anomaly eq. (25) plays an important role.

The general solution to the 't Hooft anomaly matching equations (21)-(27) can be obtained after some algebric calculations, they are

$$l_1 = \frac{K + L}{2} \qquad s_1 = \frac{- K + L}{2}$$

$$l_2 = \frac{K + M}{2} \qquad s_2 = \frac{- K + M}{2}$$

$$l_3 = \frac{D(R) + K - L + P + Q}{4} \qquad s_3 = \frac{D(R) - K - L - P + Q}{4}$$

$$l_3' = \frac{- D(R) + K + L - P + Q}{4} \qquad s_3' = \frac{-D(R) - K + L + P + Q}{4}$$

$$l_4 = \frac{D(R) + K - L}{2} \qquad s_4 = \frac{D(R) - K - L}{2}$$

$$l_5 = \frac{K + N}{2} \qquad s_5 = \frac{- K + N}{2}$$

where K, L, M, N, P and Q are integers which have to be properly choosed such that all l-type and s-type indices satisfy the constraints eqs. (19) and (20).

The arbitrariness of the index solution comes from that we allow negative s-type indices. A reasonable and natural assumption is that all s-type indices vanish

$$s_i = 0 \qquad (\text{for all } i) \tag{31}$$

With this restriction we find that

$$K = M = N = L = P = Q$$

$$D(R) = 2K \tag{32}$$

or

$$l_1 = l_2 = l_3 = l_4 = l_5 = K = D(R)/2$$

$$l_3' = s_i = m_i = 0 \qquad (\text{ for all } i) \qquad (33)$$

Therefore we finally have D(R) /2 generations of massless quarks and leptons with the following structure:

$$\begin{aligned} (u, d)_L &= (C_i\ W_a\ S) \\ (\nu, e)_L &= (C_o\ W_a\ S) \\ u_R^c &= (\overline{C}_i\ C_o\ S) \\ d_R^c &= (\overline{C}_i\ \overline{C}_o\ S) \\ e_R^c &= (\overline{C}_o\ \overline{C}_o\ S) \end{aligned} \qquad (34)$$

That means, a $SU(2)_L \times U(1)_Y$ doublet quarks or leptons is made of one chrom, one wakem and one " spinam " while a singlet quark or lepton is composed of two chroms and one " spinam ". This is another important difference from the spinor-subquark model.

§ 4 Summary and concluding remarks

The possible compositeness of quarks and leptons as a conjucture has been discussed for a long time [15]. However, it is clear that among the others the composite model of quarks and leptons can become really interesting physics only if 1) it turns out in future experiments that the composite energy scale is relatively low, and 2) the origin of color-flavors of quarks and leptons could be explained to some extent. This paper has been devoted to this topic.

a) As it has been shown, the energy scale for a gauge symmetry to be unbroken in the preon model should be lower than the composite energy scale if the composite energy scale is not vastly different from the chiral symmetry breaking energy scale. Thus we have identified the gauge part of the global chiral symmetries of the preon Lagrangian as the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ of the standard model.

b) A minimal chiral gauge theory of preons has been constructed which can be couple to the $SU(3)_C \times SU(2)_L \times U(1)_Y$ and gravity. The anomaly free conditions, vector-like charge condition and correct quantum number counting have been used to determine the color-flavor quantum numbers of the preons uniquely. Different from the most preon model so far suggested in which preons have exactly the same quantum numbers as those of one

generation of quarks and leptons, the preons in our model only have ten different color-flavors. The origin of color-flavors of quarks and leptons can be explained to some extent in terms of the color-flavors of preons.

c) By assuming the global chiral symmetry SU(10) to be spontaneously and maximally broken down to unbroken chiral subsymmetry $SU(3)_L \times SU(3)_R \times SU(2)_L \times U(1)_Y$ which minimally contains the $SU(3)_C \times SU(2)_L \times U(1)_Y$ as a subgroup, the 't Hooft anomaly matching conditions have been used to obtain index solution for massless quarks and leptons and no exotics. The generation structure of the composite fermions appears naturally.

d) With the restriction that the 't Hooft indices should be equal to or larger than zero, the number of families can be directly related to the dimension of the meta-color representation of the preons which carry the non-trivial color-flavors. In one most simple model described in section 2, the dimension D(R) is equal to six and we reproduce three generations of massless quarks and leptons.

Two remarks.

a) The chiral symmetry breaking pattern $SU(10) \longrightarrow SU(3)_L \times SU(3)_R \times SU(2)_L \times U(1)_Y$ is one of the most important assumption in this paper. It is definitely worthwhile to present some interesting scenarios in which this chiral symmetry breaking pattern can be realized in the nature.

b) There do exist the other solutions to 't Hooft anomaly matching conditions, eqs. (11)—(17), even for given unbroken chiral symmetry $SU(3)_L \times SU(3)_R \times SU(2)_L \times U(1)_Y$. Which one is favoured by the nature is obviously an open question. Recently Peccei has shown in some models that the complementarity principle and some dynamical assumptions may lead to other kind of solutions [16]. We shall discuss this issue elsewhere.

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Table Captions

Table 1	Meta-color properties of preons and the global chiral symmetries of the preon Lagrangian
Table 2	Color-flavor quantum numbers of preons
Table 3	Composite fermion spectra

Table 1

Preons	Representation of $SU(N)_{MC}$	Global chiral symmetries $SU(N+4)$ (or $SU(N-4)$)	U(1)
P_1	$\square$	$\square$	$N+2$ (or $N-2$)
P_2	$\boxed{\cdot}\boxed{\cdot}$ (or $\begin{smallmatrix}\boxed{\cdot}\\ \boxed{\cdot}\end{smallmatrix}$)	1	$-(N+4)$ (or $-(N-4)$)
Composites			
$P_1P_1P_2$	1	$\square\square$	N
$P_1P_1P_2$	1	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	N

Table 2

Preons		$SU(3)_L$	$SU(3)_R$	$SU(2)_L$	$U(1)_Y$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Q
P_1	C_i	3	1	1	1/3	3	1	1/3	1/6
	$\bar{C}_i$	1	3^*	1	-1/3	3^*	1	-1/3	-1/6
	W_a	1	1	2	0	1	2	0	(1/2, -1/2)
	$\bar{C}_o$	1	1	1	1	1	1	1	1/2
	C_o	1	1	1	-1	1	1	-1	-1/2
P_2	S	1	1	1	0	1	1	0	0

Table 3

Composites	$SU(3)_L$	$SU(3)_R$	$SU(2)_L$	$U(1)_Y$	't Hooft index	Physical identification
C_iC_jS	3^*	1	1	2/3	l_3'	d_R^c ($l_3'>0$)
C_iC_jS	6	1	1	2/3	m_1	
$\bar{C}_i\bar{C}_jS$	1	3	1	-2/3	s_3'	d_R ($s_3'<0$)
$\bar{C}_i\bar{C}_jS$	1	6^*	1	-2/3	m_2	
W_aW_bS	1	1	1	0	m_3	
W_aW_bS	1	1	3	0	m_4	
$\bar{C}_o\bar{C}_oS$	1	1	1	2	l_5	e_R^c ($l_5>0$)
C_oC_oS	1	1	1	-2	s_5	e_R ($s_5<0$)
$C_i\bar{C}_jS$	3	3^*	1	0	m_5	
C_iW_aS	3	1	2	1/3	l_1	$(u, d)_L$ ($l_1>0$)
$C_i\bar{C}_oS$	3	1	1	4/3	s_4	u_R ($s_4<0$)
C_iC_oS	3	1	1	-2/3	s_3	d_R ($s_3<0$)
$\bar{C}_iW_aS$	1	3^*	2	-1/3	s_1	$(u, d)_L^c$ ($s_1<0$)
$\bar{C}_i\bar{C}_oS$	1	3^*	1	2/3	l_3	d_R^c ($l_3>0$)
$\bar{C}_iC_oS$	1	3^*	1	-4/3	l_4	u_R^c ($l_4>0$)
$W_a\bar{C}_oS$	1	1	2	1	s_2	$(\nu, e)_L^c$ ($s_2<0$)
W_aC_oS	1	1	2	-1	l_2	$(\nu, e)_L$ ($l_2>0$)
$\bar{C}_oC_oS$	1	1	1	0	m_6	