DYNAMICAL ELECTROWEAK SYMMETRY BREAKING WITH COLOR-SEXTET QUARKS

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ABSTRACT

Under the assumption of the existence of heavy quarks belonging to a sextet representation of the color SU(3) of quantum chromodynamics we seek a possibility that the condensation of these quarks gives rise to the dynamical breaking of the electroweak SU(2)×U(1) gauge symmetry. The quantum numbers are assigned to the color-sextet quarks starting from some natural requirements. The mass of the color-sextet quarks is estimated by using the formula for the weak-boson masses. Phenomenological implications of the model are briefly discussed.

In electroweak theory an elementary scalar field, the Higgs field, is introduced to trigger the spontaneous breaking of the SU(2)×U(1) gauge symmetry. As a result we have proliferation of free parameters in the basic Lagrangian.

To resolve this unsatisfactory situation possible dynamical mechanisms of the electroweak symmetry breaking have been investigated in which the Higgs field is replaced by a bound state of some fundamental entities. A typical example of such attempts is the technicolor model proposed a decade ago by Weinberg[1] and Susskind.[2] Another attractive model of this type is the top-quark condensation model proposed recently.[3]

Here we consider yet another model of the dynamical electroweak symmetry breaking, i. e. the color-sextet-quark condensation model first proposed by Marciano.[4] In this model it is assumed that there exist heavy quarks belonging to the higher-dimensional representation of the color SU(3). The lightest of such heavy quarks is assumed to be the one in the 6-dimensional representation which we call the color-sextet quark. Their condensates play the role of the Higgs field and are responsible for the electroweak symmetry breaking.

We first determine quantum numbers of the color-sextet quarks. To do so we need some basic requirements fulfilled by these quarks Q. We require that

1. Q belongs to 6 (or 6*) of the color SU(3),
2. $\overline{Q}Q$ condenses and behaves like a Higgs field in the standard theory, i.e. $< \overline{Q}Q > \neq 0$ and $\overline{Q}Q$ ~SU(3) color-singlet, SU(2) doublet and $Y = 1$ where Y represents the hypercharge associated with U(1),
3. Q is not stable and decays into ordinary quarks and leptons. This requirement is necessary for our model to conform with present cosmological observations,
4. possible anomalies should be cancelled by adding a suitable number of extra fermions.

Let us denote the quantum numbers of fermions participating in the electroweak theory by the symbol

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(N,n,Y) where N and n represent the dimensions of the color SU(3) and weak SU(2) representation respectively. The color-sextet quark will be denoted by Q_h where index h represents the handedness.

Due to the requirement 1, we have $Q_h \sim$(6,n,Y) or (6*,n,Y). Here for later convenience we consider the case (6*,n,Y). The requirement 2 imposes the condition $\overline{Q}_k Q_h \sim$(1,2,1) where k designates the handedness opposite to h so that, if $h = L$ (left-handed), then $k = R$ (right-handed) and vice versa. According to the above condition we find that

$$Q_k = (6^*, n, Y), \quad Q_h = (6^*, n-1, Y \pm 1).$$

Although n($\geqq$ 2) is arbitrary, we fix the dimension n to be 2, the simplest possible choice. Hence

$$Q_k = (6^*, 2, Y), \quad Q_h = (6^*, 1, Y \pm 1).$$

An information on Y may be obtained through the requirement 3. We assume that the decays of Q_k and Q_h take place through one of the following effective interactions (1) $\overline{Q}^c q\overline{q}q$, (2) $\overline{q}Q\overline{q}l^c$, (3) $\overline{q}Q\overline{q}l$ and (4) $\overline{Q}^c qG$. After some arguments we find that the simplest possible choice of the quantum numbers for Q_h with $h = L$ reads

$Q_L \sim (6^*, 2, 1/3)$ for case (1) and (2),
$Q_L \sim (6^*, 2, 5/3)$ for case (3),
$Q_L \sim (6^*, 2, -1/3)$ for case (4).

The requirement 4 puts a condition on the number of extra fermions needed to cancel anomalies. In case (1) and (2) we have two extra leptons, in case (3) ten leptons, and in case (4) two extra quarks. Hence the case (3) is unreal istic with too many extra leptons and the case (4) is unreasonable since the asymptotic freedom is spoiled. We shall consider either the case (1) or (2) in the following. The decision regarding which of these two cases is acceptable will be made by experimental observations. We write

$$Q_L = (U, D)_L.$$

Our basic Lagrangian L is invariant under the local color SU(3) and electroweak SU(2)×U(1) gauge transformations. In this Lagrangian terms consisting of the color-sextet quarks and extra heavy leptons are included in addition to those of the ordinary quarks and leptons, and the Higgs field is of course absent in the Lagrangian.

The role of the Higgs field is assumed to be played by a dynamically generated bound state $\overline{Q}Q$. We, however, do not have a precise knowledge of the mechanism to form the bound state. Possibly the strong color force due to the large quadratic Casimir invariant for color-sextet quarks may be responsible for this mechanism.[4] Instead of directly dealing with the dynamics in QCD we introduce effective four-fermion interaction terms[3] including the color-sextet quarks to trigger the dynamical symmetry breaking. These four-fermion terms are constructed to be invariant under SU(3)×SU(2)×U(1) transformations. Our basic Lagrangian now reads

$$L = L_{QCD} + L_{EW} + L_4$$

where L_{QCD} is the QCD Lagrangian in which the terms consisting of color-sextet quarks are included, L_{EW} is the electroweak Lagrangian without the Higgs field, and L_4 is the four-fermion interaction Lagrangian.

We assume that the four-fermion term consisting of the color-sextet quarks is the dominant term among others triggering the condensation of color-sextet quarks. To see whether the condensation of color-sextet quarks takes place we examine the Schwinger-Dyson equation for the self-energy part of the color-sextet quark. If the Schwinger-Dyson equation allows a nontrivial solution for the self-energy part, there occurs the condensation of color-sextet quarks that signals the dynamical breaking of the electroweak symmetry.

An explicit solution may be obtained in the linearized version of the Schwinger-Dyson equation in the quenched planar approximation with the Higashijima trick[5] for incorporating the QCD running coupling constant α_s. The solution for the self-energy part Σ is given by

$$\Sigma_a(x) = m_a(\alpha_s(x)/\alpha_s(m_a^2))^{A/2}, \quad a = U,\ D,$$

where x is the Euclidean momentum squared of the color-sextet quark, m_U and m_D are the mass of the color-sextet quark U and D respectively and the exponent A is a numerical constant given by the quadratic Casimir invariant and the number of species of the triplet and sextet quarks.

Once Σ is known, the vacuum expectation value of the composite operator $\overline{Q}Q$ is calculated. Accordingly all the ferminon masses are given by this vacuum expectation value through the four-fermion terms. At the same time the gauge boson masses m_W and m_Z are given by

$$m_W = (1/2)\, g\, f_{\pi^+}, \quad m_Z = (1/2)\sqrt{g^2 + g'^{\,2}}\, f_{\pi^0},$$

where f_{π^+} and f_{π^0} are charged and neutral "pion" decay constants and g and g′ the SU(2) and U(1) coupling constant respectively. Here f_{π^+} and f_{π^0} may be calculated in terms of the self-energy part of the color-sextet quarks.[6] Hence the gauge boson masses are calculated once the color-sextet quark masses are known. Or inverting the above mass formulae one may calculate the color- sextet quark masses in terms of the gauge boson masses. Thanks to the recent precise experimental data the color-sextet quark masses are thus calculable. The predicted masses are

$$\begin{aligned} m_U &= 340 - 400 \text{ GeV}, \\ m_D &= 300 - 360 \text{ GeV}, \\ m_t &= 77 - 150 \text{ GeV}. \end{aligned}$$

In the above estimate we assumed that the top quark can condense to give a minor contribution to the dynamical mass generation. We took into account the experimental constraint on the ρ parameter and the one-loop QCD running coupling constant is employed where the scale parameter in the color-sextet mass region is obtained by using the Georgi-Politzer beta function.

Since the large Casimir invariant is assosiated with the color-sextet quarks, the e^+e^- cross section may show a big rise at the color-sextet production threshold$\sqrt{s} \sim 700$ GeV. We may observe baryons of the type Qqq with mass around 350 GeV which is color-singlet where q is the ordinary quark. The lightest of the mesons has the configuration of $Q\overline{q}\overline{q}q$. The extraordinary hadrons of the configuration $QG\overline{q}$ may also be observed at around 350 GeV where G represents the gluon. The phenomenology with the color-sextet quarks with mass around 350 GeV seems to be an exciting new field.

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DISCUSSION

Q. **P. O'Donnell** *(Univ. Toronto)*: Could you tell us about the lepton problem?

A. **T. Muta**: According to the requirement of the anomaly cancellation we need two extra lepton families. Their masses cannot be very small due to the recent experimental analysis in LEP. If their masses are large (of order 100 GeV), then they contribute to the dynamical mass generation through our four-fermion terms. Since their self-energy part is constant in our approximation, the contribution from the high energy region to the mass formula seems to be large. We are now in the process of reanalysing our estimation of masses.