PHYSICAL REVIEW D VOLUME 21, NUMBER 8 15 APRIL 1980

Exotic new quarks and dynamical symmetry breaking

William J. Marciano
The Rockefeller University, New York, New York 10021
(Received 19 December 1979)

Exotic quarks belonging to $\underline{6}$, $\underline{8}$, $\underline{10}$, or higher representations of $SU(3)_c$ (quantum chromodynamics) naturally interact more strongly than conventional $\underline{3}$-plet quarks. Therefore, chiral-symmetry breaking in exotic quark sectors may occur at much larger mass scales than ordinary chiral-symmetry breaking. If those mass scales are about 10^3 times larger, then when appended to the Weinberg-Salam model exotic quark-antiquark bound-state condensates could dynamically break the flavor $SU(2)\times U(1)$ gauge symmetry and produce viable $W^\pm$ and Z^0 masses which satisfy $M_W = M_Z \cos\theta_W$. Features of this scenario are described.

We now have an extremely attractive theory of strong interactions, quantum chromodynamics (QCD),[1] which is based on the unbroken gauge group $SU(3)_c$ associated with color. Owing to its high degree of symmetry and elegant property of asymptotic freedom,[2] QCD nicely accounts for known hadronic phenomenology and makes many perturbative predictions which can be tested at high energies, where the effective QCD coupling becomes small. In conventional QCD, each quark flavor comes in three colors, i.e., it transforms as a $\underline{3}$-plet under $SU(3)_c$, and there are (at least) six such flavors u, d, s, c, b, and t (experimental evidence for the $\underline{t}$'s existence has not yet been found).

Although at present only $\underline{3}$-plets of colored quarks are required to describe the known hadronic world, I speculate in this paper on the existence of exotic new species of quarks belonging to $\underline{6}$, $\underline{8}$, $\underline{10}$, or even higher representations of $SU(3)_c$. Phenomenological studies of such exotic quarks already exist[3-7]; however, my discussion is novel in that I examine the role they may play in dynamical symmetry breaking.

To start with, I briefly outline the basic dynamical-symmetry-breaking scenario *assumed* throughout this paper (no proof of or mechanism for its occurrence is given).[8,9] Neglecting current quark masses and electro-weak interactions, there exists in the QCD Lagrangian a separate chiral $SU(N_R)_{\rm left}\times SU(N_R)_{\rm right}$ symmetry for each distinct quark sector.[10] [N_R = number of quark flavors belonging to $\underline{R}$-plets of $SU(3)_c$, $R=\underline{3}$, $\underline{6}$, $\underline{8}$, $\underline{10}$, etc., a sector consists of all flavors with the same R.] At some value of $\alpha_s(\mu)$, the effective QCD coupling, color-singlet, quark-antiquark, bound-state condensates[11] form giving rise to a chirally asymmetric vacuum in which each chiral symmetry is broken down to $SU(N_R)$.[12] [I later argue that for distinct quark sectors, chiral-symmetry breaking may take place at different values of $\alpha_s(\mu)$.] Corresponding to each sector's chiral-symmetry breakdown, N_R^2-1 Goldstone bosons appear, which are massless quark-antiquark bound-state excitations. Appending the Weinberg-Salam (WS) $SU(2)\times U(1)$ electro-weak theory[13] to this scenario and requiring that left-handed quark components belong to SU(2) weak isodoublets and right-handed components are isosinglets, then the local $SU(2)\times U(1)$ gauge symmetry is also broken in the quark condensate vacuum down to U(1) of electromagnetism. $W^\pm$ and Z^0 gauge bosons acquire masses by absorbing three of the Goldstone bosons which become their longitudinal components. As a bonus, because of the multiplet assignments for left- and right-handed quark components [under $SU(2)\times U(1)$], the acquired masses naturally satisfy the (phenomenologically confirmed) relationship[9]

$$M_W = M_Z\cos\theta_W\,, \tag{1}$$

where θ_W is the weak mixing angle ($\sin^2\theta_W \simeq 0.23$). This scenario occurs without elementary scalar fields; so if it is realized, spontaneous symmetry breaking via Higgs scalars can perhaps be replaced by dynamical symmetry breaking.[14,15]

The scenario just described has been advocated by Weinberg and more recently by Susskind.[9] They deal only with the ordinary $\underline{3}$-plet sector of QCD and point out that chiral-symmetry breaking occurs there at about $\mu \simeq 1-2$ GeV. At that mass scale the coupling $\alpha_s(\mu)$ becomes just strong enough for bound-state condensates to form. The would-be Goldstone bosons of the $\underline{3}$-plet sector are pions (and other pseudoscalars) and their coupling to weak currents is given by (I consider the charged current and set the Cabibbo angle equal to zero)

$$\langle 0 | J_\mu^W(0) | \pi(p)\rangle = -if_\pi p_\mu\,, \tag{2}$$

where $f_\pi \simeq 130$ MeV is the pion decay constant. So if pions were responsible for giving $W^\pm$ and Z^0 their masses (they obviously are not), the resultant values would be

$$M_W = M_Z \cos\theta_W = \frac{e f_\pi}{2\sqrt{2}\,\sin\theta_W} \simeq 29 \text{ MeV}. \quad (3)$$

However, since in the WS model $M_W = 38.5/\sin\theta_W \simeq 80$ GeV, the value in (3) fails by more than three orders of magnitude. To get the masses right, the actual Goldstone boson absorbed by the W should have an $f'_\pi \simeq 2750 f_\pi \simeq 360$ GeV.

To remedy this problem, Weinberg and Susskind[9] suggest introducing a new, extra-strong interaction based on an unbroken gauge group SU(4) or larger (now called hypercolor[15]), along with new flavors of extra-strong hyperquarks belonging to its fundamental representation. Chiral-symmetry breaking in the hypercolor sector occurs at $\alpha'_s(\mu') \simeq \alpha_s(1 \text{ GeV})$ (α'_s is the hypercolor coupling) which presumably implies $\mu' \simeq 10^3$ GeV because hypercolor and color have very different β functions. So Goldstone bosons coming from chiral-symmetry breaking in the hyperquark sector can couple to the charged weak current with $f'_\pi \simeq 360$ GeV as required to get the $W^\pm$ and Z^0 masses right.[16]

I now wish to speculate that a new, extra-strong interaction may be unnecessary if exotic quarks with $\underline{R} > \underline{3}$ under ordinary $SU(3)_c$ exist. In that case chiral-symmetry breakdown in exotic sectors may occur at mass scales much larger than 1 GeV, perhaps at $\simeq 10^3$ GeV, thereby plausibly giving rise to Goldstone bosons with the required $f_{\pi_R} \simeq 360$ GeV (for $R > 3$).

The basis of my conjecture is the fact that the strength of the quark-antiquark binding potential is proportional to

$$C_2(R)\alpha_s(\mu)\,, \quad (4)$$

where $C_2(R)$ is the quadratic $SU(3)_c$ Casimir invariant of the R representation.[17] The quantity in (4) is a measure of the effective color flux linking a quark-antiquark pair at mass scale μ. Some $C_2(R)$ values for low-lying representations are

$$C_2(3) = 4/3\,, \quad C_2(6) = 10/3\,, \qquad C_2(8) = 3\,, \quad C_2(10) = 6\,. \quad (5)$$

So exotic quarks belonging to $\underline{6}$, $\underline{8}$, $\underline{10}$, etc. representations have bigger Casimir invariants than $\underline{3}$-plets (they carry more color charge) and hence interact more strongly than ordinary quarks. The weak coupling regime for ordinary $\underline{3}$-plet quarks may effectively still be a fairly strong coupling regime for exotic quarks.[18] If chiral-symmetry breaking in the $\underline{3}$-plet sector occurs at coupling strength $\alpha_s(\mu_3)$ and in the $\underline{R}$-plet sector at $\alpha_s(\mu_R)$, then the dynamical mass scales of these two sectors are related by

$$\frac{\mu_R}{\mu_3} = \exp\left[\int_{\alpha_s(\mu_3)}^{\alpha_s(\mu_R)} \frac{d\alpha_s}{\beta(\alpha_s)}\right], \quad (6)$$

where

$$\mu\frac{\partial}{\partial\mu}\alpha_s(\mu) \equiv \beta(\alpha_s) \simeq b\alpha_s^2 + O(\alpha_s^3) \text{ (perturbatively)}. \quad (7)$$

So there is a potential exponential enhancement of μ_R/μ_3 if $\alpha_s(\mu_R)$ and $\alpha_s(\mu_3)$ differ, and they are small enough for (7) to apply.

Can $\alpha_s(\mu_R)$ differ from $\alpha_s(\mu_3)$? To properly answer this question requires a better understanding of chiral-symmetry breaking in QCD than now exists. One can, however, easily envision two extreme possibilities: (1) Chiral-symmetry breaking is sector independent (or very nearly so), it does not depend sensitively on the interaction strength of the quark-antiquark pairs, only on the overall state of the QCD medium in which they are placed. In that case one would expect

$$\alpha_s(\mu_R) = \alpha_s(\mu_3) \to \mu_R = \mu_3\,. \quad (8)$$

Consequently, the "pion" decay constants of two sectors would be approximately related by[15]

$$f_{\pi_R} \simeq (R/3)^{1/2} f_{\pi_3} \simeq (R/3)^{1/2}(130 \text{ MeV})\,, \quad (9)$$

much too small a value of f_{π_R} to explain flavor symmetry breaking in the WS model. Such a scenario is uninteresting (although it may be correct[19]), so I will not discuss it further. (2) A much more interesting extreme possibility is that chiral-symmetry breaking depends entirely on the strength of the effective quark-antiquark binding potential and occurs at some critical value of the flux string tension which is common to all sectors. In that case one might expect

$$C_2(R)\alpha_s(\mu_R) = C_2(3)\alpha_s(\mu_3) \quad (10)$$

for the condition relating μ_R and μ_3. The real situation is probably much more complicated than either (8) or (10); however, the consequences which follow from (10) are so interesting that the remainder of this paper is devoted to their description. They will be relevant if it can be shown that the relationship in (10) is at least approximately valid and $\alpha_s(\mu_3)$ is small enough to start trusting perturbation theory.

Applying the condition in (10) to (6) gives

$$\frac{\mu_R}{\mu_3} = \exp\left(\int_{\alpha_s(\mu_3)}^{[C_2(3)/C_2(R)]\alpha_s(\mu_3)} \frac{d\alpha_s}{\beta(\alpha_s)}\right). \quad (11)$$

To estimate this quantity, I assume that α_s is small enough throughout the region of integration in (11) so that only the first term in the β function of (7),

$$b = -\frac{1}{2\pi}\left(11 - \tfrac{2}{3}N_3 - \tfrac{10}{3}N_6 - 4N_8 - 10N_{10} + \cdots\right), \quad (12)$$

TABLE I. Values of μ_R/μ_3, for $R=6$, 8, and 10 predicted by (13) for a range of $\alpha_s(\mu_3)$ values.

$\alpha_s(\mu_3)$	μ_6/μ_3	μ_8/μ_3	μ_{10}/μ_3
0.40	29	17	2580
0.35	47	25	7910
0.30	89	42	3.5×10^4
0.25	218	89	2.9×10^5
0.20	839	273	6.6×10^6
0.15	7910	1772	1.2×10^9
0.10	7×10^5	7.5×10^4	4.4×10^{13}

need be used. I take $N_3=6$ and neglect exotic quark contributions in (12). This gross oversimplification is a bad approximation near the lower and upper regions of integration in (11) because it ignores both ordinary "heavy" quark (c,b,t) threshold effects and new exotic quark thresholds. Fortunately, these two defects cancel (to some extent) and become less important for μ_R/μ_3 very large, the case of interest to us. Applying these approximations to (10) gives

$$\frac{\mu_R}{\mu_3}\simeq\exp\left[\frac{2\pi}{7\alpha_s(\mu_3)}\left(\frac{C_2(R)}{C_2(3)}-1\right)\right]. \tag{13}$$

Numerical estimates obtained from (13) are very sensitive to the value of $\alpha_s(\mu_3)$ employed. To get a reasonable estimate, I list in Table I values of μ_R/μ_3 corresponding to a realistic range of $\alpha_s(\mu_3)$ for $\mu_3\simeq O(1\text{ GeV})$. Notice the wide spread in the possible values μ_R/μ_3. Unfortunately, $\alpha_s(\mu_3)$ is not really well known and it is not clear what exactly is the scale of ordinary chiral-symmetry breaking. In any case, the values in Table I point out that if the premise in (10) is approximately correct, then $\mu_R/\mu_3\simeq10^3$ is not unreasonable. That would in turn imply that Goldstone bosons resulting from the breakdown of chiral symmetry in an exotic quark sector could have $f_{\pi_R}\simeq360$ GeV. The last step in this scenario, is that if such exotic quark flavors are appended to the standard $SU(3)_c\times SU(2)\times U(1)$ model as left-handed doublets and right-handed singlets under SU(2), they can provide a dynamical symmetry breakdown to $SU(3)_c\times U(1)$ and give viable masses to the $W^\pm$ and Z^0, which satisfy $M_W=M_Z\cos\theta_W$.

Accepting the premise in (10) and subsequent scenarios, what happens to asymptotic freedom in QCD? From (12) we observe that for $N_3=6$, QCD can accomodate just two $\underline{6}$-plets and still retain asymptotic freedom (fortunately this is enough to have an exotic chiral flavor symmetry). Two flavors of $\underline{8}$-plets, $\underline{10}$-plets, or higher representations added to QCD with $N_3=6$ destroy asymptotic freedom. So we must be content with only adding two $\underline{6}$-plets, look for a larger group in which to embed QCD that can accommodate additional exotic flavors, or give up asymptotic freedom. In the second case, one is encouraged by the fact that exotic representations (especially $\underline{6}$-plets) arise quite naturally in grand unified theories.[5,7] I will not discuss grand unification. Instead, as a concrete illustration of the exotic-quark idea, I now describe some aspects of simply adding two $\underline{6}$-plets to the standard model.

Consider the addition of two $R=\underline{6}$ QCD sextets, denoted by U and D (color indices suppressed), to the WS model[13] (without elementary Higgs scalars[14]) as a left-handed doublet and two right-handed singlets:

$$\begin{pmatrix}U\\D\end{pmatrix}_L,\ U_R,D_R. \tag{14}$$

For simplicity, I assign electric charge $+2/3$ to the U and $-1/3$ to the D, in which case anomalies may be canceled by also adding two new sequential lepton doublets. Assuming that (10) is approximately correct and that $f_{\pi_6}\simeq360$ GeV, then the three Goldstone bosons resulting from the breakdown of chiral $SU(2)_L\times SU(2)_R$ in the exotic quark sector become longitudinal components of the $W^\pm$ and Z^0 and provide masses $M_W=M_Z\cos\theta_W=ef_{\pi_6}/(2\sqrt{2}\sin\theta_W)\simeq80$ GeV. A residual bound-state pseudoscalar associated with $U_A(1)$ in the exotic sector will exist; its mass will presumably be quite large, $\simeq10^3$ GeV. There is an extremely rich phenomenology of new hadronic physics that results from the addition of these two $\underline{6}$-plets, including the exciting possibility of new, very massive stable hadrons. Many of the phenomenological consequences have been discussed in the literature,[3-7] so I will not review them here.

The conjecture that chiral-symmetry breaking in distinct quark sectors occurs at different values of $\alpha_s(\mu)$ and consequently extremely different mass scales is very speculative but quite interesting. My discussion is primarily intended to open up a dialogue on this subject and point out some of the consequences that could follow from it. Further examination of this possibility may help us to better understand ordinary chiral-symmetry breaking even if the exotic-quark idea is wrong. Before the scenario I have described can be taken seriously, several questions must be answered. Can the condition in (10) actually be realized in a viable description of chiral-symmetry breaking? What is $\alpha_s(\mu_3)$? Is the naive perturbative approach of (13) applicable? Can the ratio $\mu_R/\mu_3\simeq10^3$ be sustained, or will distinct sectors couple and destabilize this mass hierarchy? These and related questions are being investigated.

ACKNOWLEDGMENTS

I wish to thank my colleagues at The Rockefeller University, especially M.A.B. Bég, A. Carter, H. Pagels and H.–S. Tsao for discussions and comments on the ideas presented in this paper. My work was supported in part by the U.S. Department of Energy under Contract Grant No. EY-76-C-02-2232B. *000.

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[1]For a review of QCD see W. Marciano and H. Pagels, Phys. Rep. 36C, 137 (1978).

[2]H. D. Politzer, Phys. Rev. Lett. 30, 1346 (1973); D. Gross and F. Wilczek, *ibid.* 30, 1343 (1973).

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[8] Classic discussions of dynamical symmetry breaking are Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961); J. Schwinger, *ibid.* 125, 397 (1962); 128, 2425 (1962). Applications to modern gauge theories are given in R. Jackiw and K. Johnson, Phys. Rev. D 8, 2386 (1973); J. Cornwall and R. Norton, *ibid.* 8, 3338 (1973).

[9]S. Weinberg, Phys. Rev. D 13, 974 (1976); 19, 1277 (1979); L. Susskind, *ibid.* 20, 2619 (1979). These papers present a detailed description of the dynamical-symmetry-breaking scenario I employ; they inspired the ideas presented here.

[10]Each sector also has a $U_V(1)\times U_A(1)$ symmetry which I neglect. The $U_V(1)$ corresponds to "sector" number conservation, while a linear combination of the $U_A(1)$'s is broken by triangle anomalies in the presence of instantons: see G. 't Hooft, Phys. Rev. Lett. 37, 8 (1976).

[11]By quark condensate I mean $\langle 0 \mid \bar{q}q \mid 0\rangle \neq 0$.

[12]The occurrence of dynamical symmetry breaking in QCD has not been proved. One interesting possibility recently advocated is that instantons produce such an effect. C. Callan, R. Dashen and D. Gross, Phys. Rev. D 16, 2526 (1977); 17, 2717 (1978); D. Caldi, Phys. Rev. Lett. 39, 121 (1977); R. Carlitz, Phys. Rev. D 17, 3225 (1978).

[13]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm 1968), p. 367.

[14]Ultimately, one must show how lepton and current quark masses are generated in this scenario. For the time being I assume that will naturally occur when new (sector changing) interactions are introduced either by grand unification or condensate coupling; see Ref. 9.

[15]M. A. B. Bég, H. D. Politzer, and P. Ramond, Phys. Rev. Lett. 43, 1701 (1979).

[16]It is assumed that $f'_\pi/f_\pi \simeq \mu'/1$ GeV up to an overall factor of $O(1)$.

[17]D. Gross and F. Wilczek, Phys. Rev. D 8, 3633 (1973).

[18]Since gluons belong to an 8-plet, their color interaction is stronger than that of ordinary quarks; therefore perturbation theory should be less reliable for gluonic systems (e.g., gluon bound states, gluon jets, etc.). Cf. K. Shizuya and S. Tye, Phys. Rev. Lett. 41, 787 (1978); M. Einhorn and B. Weeks, Nucl. Phys. B146, 445 (1978).

[19]Chiral-symmetry breaking via instanton effects, as described in Ref. 12, would seem to favor (8) over (10). I thank H.-S. Tsao for discussions on this question.