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Experimental Characteristics of Dynamical Pseudo Goldstone Bosons

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The hypothetical existence of new color interactions, which participate in the spontaneous breaking of the weak-interaction group, will in general lead to relatively light composite pseudo Goldstone bosons. Their production and decay characteristics are analyzed to be close to, yet actually distinguishable from, those of the elementary Higgs bosons of the Weinberg-Salam model.

The usual implementation of the Goldstone-Higgs mechanism of spontaneous symmetry breaking, via elementary spin-0 fields, is one of the less attractive features of conventional quantum flavordynamics (QFD). And the situation is acute in attempts to unify QFD and quantum chromodynamics (QCD) into a single gauge theory. In such grand unified theories, one is obliged to introduce a multitude of Higgs fields with judiciously contrived couplings; the essential simplicity of the gauge-theoretic approach is, thereby, irretrievably lost. It has been suggested,[1-4] therefore, that one discard elementary Higgs fields altogether, and seek a dynamical mechanism for symmetry breakdown.

In the simplest dynamical mechanism, the requisite Goldstone bosons, which furnish the longitudinal degrees of freedom for massive gauge fields, are bound states of a new species of quark, whose superstrong gauge interactions (generated by gauging a color′ degree of freedom and described by a theory hereinafter called QC′D) spontaneously break chiral symmetry.

The color′ quarks are likely to come in several flavors, in which case there will be several light pseudo Goldstone bosons as well. In this Letter we observe that these particles may be as light as 10 GeV, that they will be relatively pointlike (of size 1 TeV^{-1}), and will have production and decay modes that are determined by partial conservation of axial-vector-current arguments and hence are fairly model independent. Their signatures are, crudely speaking, similar to those of elementary Higgs particles; consequently, we stress the differences. If spin-0 weakly interacting particles are discovered with masses of tens of GeV, the question of composite versus elementary need not wait until energies of 1 TeV probe the possible bound-state structure.

The color′ degree of freedom, first introduced by Weinberg,[3] may be dubbed "hypercolor."[4] The terminology is convenient, with words such as hyperquark, hyperpion, and hyper-σ having an obvious meaning. We take the weak and electromagnetic interactions of the hyperquarks to be isomorphic to those of ordinary quarks so that a flavor doublet such as (u', d') transforms as (u, d) under the electroweak group.

The existence of hyperquarks is, of course, logically independent of the existence of elementary Higgs particles; we do not rule out the possibility that there may exist both hyperpions and elementary weak scalars. In such a case, $f_{\pi'}$ (the hyperpion decay constant) need not be as large as suggested below, and hypercolor would be even more accessible at low energies. However, careful attention must be paid to mixing to identify the physical states and analyze their decays.[5] Our discussion of hyperpions would still be applicable and would be an aid in deciphering which was which.

Three of the hyperpions must be exactly massless to be absorbed by the $W^{\pm}$ and Z, and in the process they contribute to the W and Z masses:

$$m_Z \cos\xi = m_W \cong \tfrac{1}{2} e f_{\pi'} \sin\xi, \tag{1}$$

where e is the unit of electric charge and ξ is the Glashow-Weinberg-Salam angle.[1] Hence $f_{\pi'} \cong 300$ GeV. (Note that the relationship between W and Z masses, embodying the so-called $\Delta I_{\text{weak}} = \frac{1}{2}$ rule, emerges naturally.) In the following, we shall assume that QC′D may be regarded as scaled-up QCD, albeit with a different number of colors; the characteristic mass scales, Λ' and Λ, in the two theories may, therefore, be related via

$$f_{\pi'}/\Lambda'(N_{C'})^{1/2} = f_\pi/\Lambda(N_C)^{1/2}, \tag{2}$$

where N_C is the number of quark colors. Since $\Lambda \sim 300$ MeV, we have $\Lambda' \sim (3/N_{C'})^{1/2}$ TeV.

No completely satisfactory hypercolor model of dynamical symmetry breaking exists as yet. There are several outstanding problems: (i) While $f_{\pi'}$ gives mass to the W's, quarks and leptons must get their masses elsewhere.[6] (ii) Lifting the mass degeneracy within weak isospin quark doublets appears—at least in the simplest models for generating fermion mass—to destroy the $\Delta I_{\text{weak}} = \frac{1}{2}$ relation between W and Z masses.[7] (iii) Unified models typically have many hyperquarks,[8] and hence many massless, unabsorbed hyperpions.

We proceed assuming that these problems are solvable and, in particular, that the unabsorbed hyperpions acquire masses; the order of magnitude of these masses may be estimated as follows. Current-algebra considerations imply that the near-Goldstone modes in QC′D and QCD satisfy

$$m_{\pi'}^2 = m_\pi^2 \frac{m_{q'}}{m_q} \frac{\langle 0|\bar{q}'q'|0\rangle}{f_{\pi'}^2} \frac{f_\pi^2}{\langle 0|\bar{q}q|0\rangle}. \tag{3}$$

Also, since QC′D is presumed to be scaled-up QCD, we may equate the dimensionless ratios

$$\frac{\langle 0|\bar{q}'q'|0\rangle}{N_{C'}\Lambda'^3} = \frac{\langle 0|\bar{q}q|0\rangle}{N_C\Lambda^3}. \tag{4}$$

Equations (2)–(4) yield

$$m_{\pi'}^2 = m_\pi^2 \frac{m_{q'}}{m_q} \frac{f_{\pi'}}{f_\pi} (\tfrac{3}{4})^{1/2}, \tag{5}$$

using three colors for QCD and assuming four for QC′D, respectively. For $m_{q'} \sim m_q$, e.g., if the current quark masses are of a similar origin, Eq. (5) implies $m_{\pi'} \sim 7$ GeV. This estimate is to be contrasted with the naive expectation for pseudo-Goldstone-boson[9] masses arising at the one-loop level: $m_{\pi'} \sim \alpha^{1/2} f_{\pi'} \cong 25$ GeV. (Later, where a specific numerical value is required, we take $m_{\pi'} \sim 15$ GeV.)

As pseudo Goldstone bosons, the hyperpions have fairly model-independent decay modes since they couple primarily to the divergences of currents. To the extent that these currents contain contributions from the known quarks and leptons, these divergences will be of the form

$$\partial_\mu j_5^{\ \mu} = \ldots + (m_i + m_j)\bar{f}_i \gamma_5 f_j, \tag{6}$$

$$\partial_\mu j^\mu = \ldots + (m_i - m_j)\bar{f}_i f_j, \tag{7}$$

where m_i is the mass of the fermion f_i. The hyperpion couplings are to be contrasted with those of the left-over elementary Higgs scalar φ of the Weinberg-Salam model:

$$\mathcal{L} = \ldots + (1/\langle\varphi\rangle)\varphi m_i \bar{f}_i f_i. \tag{8}$$

Thus both types of bosons have the strongest couplings to the heaviest fermion available, but there are measurable differences. For instance, a flavor-diagonal decay of the π' is S wave, while that of φ is P wave leading to the difference in branching ratios:

$$\frac{\Gamma(\varphi \to b\bar{b})}{\Gamma(\varphi \to \tau\bar{\tau})} \cong 3\left(\frac{m_b}{m_\tau}\right)^2 \left(\frac{m_\varphi^2 - 4m_b^2}{m_\varphi^2 - 4m_\tau^2}\right)^{3/2}, \tag{9}$$

$$\frac{\Gamma(\pi' \to b\bar{b})}{\Gamma(\pi' \to \tau\bar{\tau})} \cong 3\left(\frac{m_b}{m_\tau}\right)^2 \left(\frac{m_{\pi'}^2 - 4m_b^2}{m_{\pi'}^2 - 4m_\tau^2}\right)^{1/2}. \tag{10}$$

Furthermore, if we look at exclusive channels, processes such as $\varphi \to D\bar{D}$ and $\pi' \to D\bar{D}\pi$ are allowed, whereas $\varphi \to D\bar{D}\pi$ and $\pi' \to D\bar{D}$ are forbidden.

The 2γ decay of neutral hyperpions can be computed, as for π^0, from the triangle anomaly:

$$\frac{\Gamma(\pi'^0 \to 2\gamma)}{\Gamma(\pi^0 \to 2\gamma)} = \left(\frac{f_\pi}{f_{\pi'}}\right)^2 \left(\frac{m_{\pi'}}{m_\pi}\right)^3 \frac{4}{3}, \tag{11}$$

modulo possible differences in q' and q charges. However, the branching ratio to 2γ is likely to be very small compared to the decay to massive fermions $\bar{f}f$:

$$\frac{\Gamma(\pi'^0\to 2\gamma)}{\Gamma(\pi'^0\to\bar{f}f)} \propto e^4\left(\frac{m_{\pi'}}{m_f}\right)^2\times(\text{phase-space ratio}). \qquad (12)$$

The hyperpions are of size Λ'^{-1} or $f_{\pi'}^{-1}$. The charged π''s, therefore, will be produced liberally in e^+e^- annihilation; the deviation from

$$R_{e^+e^-}(s)=\tfrac{1}{4}\sum_{\pi'}Q_{\pi'}^2(1-4m_{\pi'}^2/s)^{3/2} \qquad (13)$$

is of order $N_{\pi'}s/f_{\pi'}^2$, where $N_{\pi'}$ is the number of charged hyperpions, $Q_{\pi'}$ are their electric charges, and $s\equiv(\text{c.m. energy})^2\ll f_{\pi'}^2$. That the departure from the pointlike limit, Eq. (13), is of the order stated may be verified by writing an *effective* chiral Lagrangian[3] for the π''s.

In fact, all of the couplings of π''s can be deduced using an effective-Lagrangian approach, as long as the π''s are soft, on the scale set by $f_{\pi'}$. For simplicity we imagine using linear representations with the pseudoscalar π''s accompanied by scalar σ''s. From the implicit q' content of the π' and from the W and Z masses that now come from σ' vacuum-expectation values, it is evident that the chiral quadruplets transform as complex doublets, Φ's, under the electroweak group:

$$\Phi=\begin{pmatrix} i\pi'^+ \\ \tfrac{1}{2}\sqrt{2}(\sigma'-i\pi'^0)\end{pmatrix}. \qquad (14)$$

The relevant couplings can be read off from

$$\mathcal{L}_{\text{eff}}=(D^\mu\varphi)^\dagger(D_\mu\varphi)+\ldots, \qquad (15)$$

where D_μ is the appropriate gauge-covariant derivative. Note that now

$$\langle\sigma'\rangle=f_{\pi'}\approx 300\text{ GeV}. \qquad (16)$$

From this standpoint, the "soft" couplings of π' and σ' resemble a model with several elementary Higgs fields, where the physical spin-0 particles include not only the scalar Higgs particle of the minimal Weinberg-Salam model but also additional scalars and pseudo-Goldstone pseudoscalars. The distinction lies in the expected masses. The masses of fundamental spinless particles are typically comparable to each other. In contrast, a dynamical σ' would have a mass of order Λ', ~1–3 TeV by analogy with QCD, and its decays into light π''s would be so fast as to make it virtually unrecognizable as a distinct particle. Hence, the prominent light particles are all pseudoscalars.

We exhibit the contrasts in some simple models. The coupling of π''s to a lepton or quark doublet (a,b), mediated by $W^\pm$ and Z, are described by the effective interaction

$$\mathcal{L}_{\text{eff}}=(G_F/\sqrt{2})f_{\pi'}\sqrt{2}\,\bar{a}[(m_a-m_b)-\gamma_5(m_a+m_b)]\,b(-i)\pi'^+ +\text{H.c.} + (G_F/\sqrt{2})f_{\pi'}2(m_a\bar{a}i\gamma_5 a-m_b\bar{b}i\gamma_5 b)\pi'^0. \qquad (17)$$

Note that the σ' does not couple directly to a or b and, therefore, it is not responsible for their masses. Note also the *universality* of π' couplings to any doublet: Apart from the trivial mass rescaling, the coupling to (c,d) is the same as that to (a,b).

The contrast with the minimal standard model, in which

$$\mathcal{L}_1=+\frac{e}{2m_W\sin\xi}(m_a\bar{a}a+m_b\bar{b}b)\varphi^0, \qquad (18)$$

is discussed above [e.g., Eqs. (9) and (10)]. Consider then a variant with an additional Higgs doublet (a total of five physical spin-0 fields):

$$\mathcal{L}_2=\mathcal{L}_1+2^{-1/2}(f_1\bar{a}a+f_2\bar{b}b)\eta^0+2^{-1/2}(-f_1\bar{a}i\gamma_5 a+f_2\bar{b}i\gamma_5 b)\chi^0+\tfrac{1}{2}\bar{a}[(f_2-f_1)+\gamma_5(f_2+f_1)]\chi^+ +\text{H.c.} \qquad (19)$$

There is no universality here relating the f's of one fermion doublet to those of another. A further contrast to the dynamical scheme is the presence of two relatively light neutrals which undergo P-wave decays. Needless to say, the distinctions would be blurred if, for some reason, the f's are universal and equal to the would-be π' couplings and if φ and η not only have masses of order 1 TeV but also manage to decay *strongly* into pairs of pseudoscalar mesons.

We have discussed some experimental consequences of hypercolor interactions that would be manifest at energies well below typical hyperhadron masses; these low-energy consequences, follow from partial conservation of axial-vector-

TABLE I. Some characteristics of spin-0 particles which occur in theories with a dynamical Higgs mechanism [σ', π'^0, $\pi'^\pm$] and in theories with elementary Higgs fields [φ^0, χ^0, $\chi^\pm$]. The φ decay rates quoted are for $m_\varphi = 15$ GeV. Note that σ', the dynamical analog of φ^0, decays rapidly to $\pi'^+\pi'^-$, etc., via *strong* interactions.

PARTICLE	EXPECTED MASS (in GeV)	FEASIBLE PRODUCTION MECHANISM	2γ DECAY		f $\bar{f}$ DECAYS				PSEUDOSCALAR MESON CHANNELS	
			Rate (in sec^{-1})	Photon Pols.	Universal Coupling	$\nu_\tau \tau$ Rate (in sec^{-1})	$\tau\bar{\tau}$ Rate (in sec^{-1})	$\Gamma(b\bar{b})/\Gamma(\tau\bar{\tau})$	$D\bar{D}$	$D\bar{D}\pi$
σ'	~2000	?	-	-	-	-	-	-	-	-
π'^0	~15	Via Heavy Flavors in $e^+e^-\to$. . . or $pp\to$ . . . .; $W^\pm \to \pi'^\pm\pi'^0$	~2×10^{15}	$\perp$	Yes	-	~10^{20}	~15	No	Yes
$\pi'^\pm$	~15	$e^+e^-\to\pi'^+\pi'^-$; $W^\pm\to\pi'^\pm\pi'^0$	-	-	Yes	~3×10^{19}	-	-	Yes	Yes
ϕ^0	$\gtrsim$10	Via Heavy Flavors and Virtual W-Pairs in $e^+e^-\to$.. or $pp\to$ ...	$\lesssim10^{17}$	$\parallel$	Yes	-	~4×10^{19}	~10	Yes	No
χ^0	Could be ~15	Same as for π'^0	?	$\perp$	No	-	?	?	No	Yes
$\chi^\pm$	Could be ~15	Same as for $\pi'^\pm$	-	-	No	?	-	-	Yes	Yes

current arguments and are therefore fairly insensitive to how hypercolor is implemented. We have also contrasted the experimental profile of relatively low-lying dynamical bosons, in the hypercolor scenario, with that of elementary Higgs particles. (Some of our results are summarized in Table I.) It is our hope that our experimental colleagues will be able to shed some light on the nature of the Higgs mechanism in the not-too-distant future.

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