IC/75/139

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

ARE QUARKS COMPOSITE?

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INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

1975 MIRAMARE-TRIESTE

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UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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ADDENDUM
TO
IC/75/139

ARE QUARKS COMPOSITE? *

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A simpler scheme of PREONS, of which all quarks can be composite, is obtained as follows.

(1) Identify the four valency/flavour (I-spin up, down, strange and charmed) PREONS with physical leptons. Thus the valency/flavour PREONS are

$$L_L = (\nu_e, e^-, \mu^-, \nu_\mu)_L \quad ,$$

$$L_R = (\nu_e, e^-, \mu^-, \nu_\mu)_R \quad .$$

The L's carry baryon number $\mathcal{B} = 0$ and lepton number $\mathcal{L} = 1$.

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* To appear in Physics Letters B.

5743

(2) Assume there exist three (red, yellow and blue) spin $\frac{1}{2}$ colour PREONS ("colorons") belonging to a triplet of $SU(3)_{colour}$, and one singlet spin $\frac{1}{2}$ PREON $\mathcal{S}^0$. The red, yellow and blue quarks are then $L\mathcal{S}\overline{\mathcal{C}}$ composites, **provided the** lepton-number, baryon-number assignments of $\mathcal{S}$ and $\mathcal{C}$ follow one of the schemes below:

	$\mathcal{L}$	$\mathcal{B}$
$\mathcal{S}$	0	1
$\mathcal{C}$	1	0

OR

	$\mathcal{L}$	$\mathcal{B}$
$\mathcal{S}$	-1	0
$\mathcal{C}$	0	-1

with electric charges $Q_{\mathcal{S}} = 0$, $Q_{\mathcal{C}} = (0,-1,-1)$

OR $Q_{\mathcal{S}} = -1$, $Q_{\mathcal{C}} = (1,0,0)$,

for either of the two schemes above. Thus there are a total of eight four-component PREONS (= 16 two-component PREONS) of which six (two-component) ones are the known leptons.

The "old" mesons, $\pi, \rho, \ldots$, are colour singlet $\bar{q}q$ q = quark composites, while <u>some</u> of the new mesons J/ψ may be $\mathcal{C}\overline{\mathcal{C}}$ or $\mathcal{C}\overline{\mathcal{C}}\,\mathcal{S}\overline{\mathcal{S}}$ composites.

In this model quark-lepton transitions are immediate, if theory permits expectation values of spin-zero fields like $(\mathcal{S}\overline{\mathcal{C}})$ to be non-zero (e.g. if $\langle \mathcal{S}\overline{\mathcal{C}} \rangle \approx 10^{-9} (\mathrm{GeV})^2$ then quarks of around $2 \sim 3$ GeV would live $\approx 10^{-11}$ secs.). <u>The SLAC $\mu^{\pm} e^{\mp}$ events could result from such decays of quarks or colorons into leptons.</u>

A gauge theory based on $[U(1) \times SU_L(2) \times SU_R(2)] \times [SU'(3) \times U'(1)]$ can be built up, similar to that presented in the paper with $L_L = (2+2,1,1)_{1,0}$, $L_R = (1,2+2,1)_{1,0}$, $\mathcal{C} = (1,1,3)_{0,1}$, $\mathcal{S} = (1,1,1)_{-4,3}$, where the subscripts show the $U(1) \times U'(1)$ assignments, and the charge formula is

$$Q_{electric} = I_{3L} + I_{3R} + F'_3 + \frac{1}{\sqrt{3}} F'_8 - \frac{1}{2} I_0 - \frac{2}{3} I'_0 \quad .$$

(This formula corresponds to the assignments $Q_{\mathcal{C}} = 0,-1,-1$ and $Q_{\mathcal{S}^0} = 0$.) The photon is expressed as:

$$\frac{1}{e} A = \frac{1}{g}(W_L + W_R) + \frac{1}{f}(V_3 + \frac{1}{\sqrt{3}} V_8) + \frac{1}{2h} T + \frac{2}{3h'} T' \quad .$$

It is conceivable that by an appropriate choice of the couplings h and h' and the masses of the corresponding gluons T and T' , one can arrange that for (photo- and lepto-production) experiments, which in this gauge model excite valency degrees of freedom (and fractional charges) only, the probing photons are sensible of light leptonic masses only inside the quarks. To incorporate heavy leptons (and extra quarks) in the model, there are two alternatives. If the number of extra heavy leptons is two, it may be simplest to increase the fundamental valency multiplet from a quartet $(\nu_e, e^-, \mu^-, \nu_\mu)$ to a six-fold with charges $(0,-1,-1,0,0,-1)$ as suggested by several authors (Harari, Barnett, De Rujula, Georgi, Glashow, Fritzsch, Minkowski and Gell-Mann). There are now altogether ten PREONS (with three "colorons" $\mathcal{C}$ and one singlet $\mathcal{S}^0$ and $\sum_{\text{PREONS}} Q^2 = 5$). Alternatively, if the number of new heavy leptons is four, it may be more economical to leave the leptonic valency PREONS as a quartet, but to add on an extra singlet $\mathcal{S}_H$ with the same leptonic and baryonic number assignments as $\mathcal{S}$. In this case the new heavy leptons could be $L\mathcal{S}\bar{\mathcal{S}}_H$ composites. With charge assignments $Q_{\mathcal{C}} = (1,0,0)$ and $Q_{\mathcal{S}} = Q_{\mathcal{S}'_H} = -1$, we again reach $\sum_{\text{PREONS}} Q^2 = 5$.

The PREON idea has previously been discussed by W. Królikowski (Bull. Acad. Polon. Sci. 20, 487 (1972)).

IC/75/139

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ABSTRACT

It is suggested that quarks and leptons are composites of still more fundamental PRE-entities.

MIRAMARE - TRIESTE
September 1975

* To be submitted for publication.

An elegant economy was introduced in hadron physics when Gell-Mann and Zweig invented the quark. Each quark represented one "valency attribute": I-spin up, I-spin down and strangeness. All hadrons were assumed to be quark composites. The original three valency attributes have since presumably increased to four with the inclusion of charm. Another extension, the inclusion of three colours was needed principally to resolve a spin-statistics dilemma. Most theorists thus believe in twelve fundamental quarks representing seven fundamental attributes (four valencies and three colours). Another doubling, to twenty-four quarks, has been suggested recently [1] to accommodate the "mirror" quantum number which may be needed to give a description of J/ψ particles. If lepton number is counted as a fourth colour [2] one would arrive at the need for a thirty-two component fundamental fermion of which all matter is made.

Clearly the time has come to consider alternative ways of accommodating the fundamental attributes. It could prove useful to regard the quarks themselves as composite structures and our purpose here is to sketch a model based on entities which may be more basic than quarks. These entities we shall call PRE's, and of them the thirty-two quarks are supposed to be made.*) To represent the PRE's a pair of quartets is needed. One, the <u>valency quartet</u> $Q = (pn\lambda\chi)$, serves to carry the usual SU(3) quantum numbers and charm. The other, the <u>colour quartet</u>, $\mathcal{C} = (abcd)$, carries the quantum numbers of $SU(3)_{colour}$ and lepton number. There are two possible variants:

(A) Q is a fermion and $\mathcal{C}$ a boson **). The sixteen states ***), $Q\bar{\mathcal{C}}$, are two-body composites and, of course, fermionic.

(B) One may introduce a neutral PRE singlet fermion, $\mathcal{S}$. It is then possible to envision another variant in which the quarks and leptons appear as three-particle composites ***), $Q\bar{\mathcal{C}}\mathcal{S}$.

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*) The idea of PRE's was motivated by Pati and Salam, Refs.1 and 2. A similar idea for quarks but not for leptons has been independently considered with a different motivation by Greenberg, Ref.3, who gives references to earlier work.

**) This would ensure that strong interactions, generated by colour-gauge symmetry are necessarily vector and thus parity conserving.

***) To incorporate the "mirror"(or "heaviness") quantum number, introduce one additional electrically neutral singlet PRE $\mathcal{S}'$. In this case the "mirror" (heavy) quarks are $Q\bar{\mathcal{C}}\mathcal{S}'$ composites.

We present a gauge model for (B) which, with minor modifications, can be adapted for (A) as well.

Although the largest group structure admitted by the kinetic energy term of nine PRE's is $U_L(1) \times U_R(1) \times SU_L(4) \times SU_R(4)$, we choose to work with symmetry $(SU(4)_L \times SU(4)_R \times U(1))_{valence} \times (SU(4) \times U(1))_{colour}$ which appears to reflect the underlying dynamics more closely. To avoid problems with anomalies, we shall restrict the valence (local) symmetry $SU(2)_L \times SU(2)_R \times U(1)$. The presence of two U(1)'s serves two ends. Firstly, these contribute to the PRE charges which can therefore be assigned integer values.*) Secondly, the U(1)'s provide gauge couplings for the neutral singlet $\mathcal{S}$ with itself and with Q's and $\mathcal{C}$'s so that the composites, $Q\bar{\mathcal{C}}\mathcal{S}$, can appear as bound states. We assign particles as follows:

$$Q_L = (2+2,1,1)_{1,0} \;,\; Q_R = (1,2+2,1)_{1,0} \;,\; \mathcal{C} = (1,1,4)_{0,1} \;,\; \mathcal{S} = (1,1,1)_{-1,1} \tag{1}$$

(Here the $U(1)_{valence} \times U(1)_{colour}$ assignments are shown as subscripts.) The charge operator

$$Q_{electric} = I_{3L} + I_{3R} + F_3' + \frac{1}{\sqrt{3}} F_8' - \sqrt{\frac{2}{3}} F_{15}' - \frac{1}{2} I_0 - \frac{1}{2} I_0' \tag{2}$$

takes the form diag(0,-1,-1,0) on the quartets and of course vanishes on the singlet. Notice that the $U(1) \times U(1)$ quantum numbers assigned to $\mathcal{S}$ are opposite to those on Q and $\bar{\mathcal{C}}$ and so would yield attractive gluon forces in the composite $Q\bar{\mathcal{C}}\mathcal{S}$.

A Lagrangian model for the PRE's with couplings mediated by gauge fields (whose masses are generated by a Higgs mechanism) is easily constructed. The valence symmetry, $SU(2)_L \times SU(2)_R \times U(1)$ is associated with two triplets, W_L, W_R, and a singlet, T, while the colour symmetry $SU(4) \times U(1)$ is associated with a 15-fold. V, and a singlet T'. To generate masses for these vector fields we shall take the Higgs-Kibble set:

$$A = (4,\bar{4},1)_{0,0} \;,\; B = (1,4,\bar{4})_{1,-1} \;,\; C = (\bar{4},1,4)_{-1,1} \;,\; D = (1,1,4)_{0,1} \;. \tag{3}$$

*) This is admittedly a prejudice. If the U(1)'s are discarded, then the quartet PRE's would carry electric charges $\pm \frac{1}{2}$. Note that the total U(1) charge on quarks or leptons is zero.

The subset consisting of A,B and C has been analysed previously (on the assumption that the dominant terms in the potential are invariant under the full global symmetry $(U(4)_L \times U(4)_R)_{valence} \times U(4)_{colour}$). Here, because of the singlets T and T' it is necessary to include a fourth multiplet, D (to which we assign the quantum numbers of the colour PRE), in order that the only residual symmetry shall be the electromagnetic U(1).

The Higgs potential can be taken in such a way as to force the vacuum expectation values into the forms,

$$\langle A \rangle = \mathrm{diag}(a_1,a_1,a_1,a_4) \;,\; \langle B \rangle = \mathrm{diag}(0,0,0,b_4) \;,$$
$$\langle C \rangle = \mathrm{diag}(c_1,c_1,c_1,c_4) \;,\; \langle D \rangle = (0,0,0,d) \;. \tag{4}$$

Physical considerations (which apply as much to the model of Ref.1 as to the present one) give the scale $b \sim 10^4 - 10^5$ GeV; $a \sim 300$ GeV; $c \sim 1$ GeV. The mass term for Fermi particles is taken in the form $m_c \bar{\mathcal{C}}\mathcal{C} + m_s \bar{\mathcal{S}}\mathcal{S} + K\, \bar{Q}_L A^+ Q_R$ + h.c. (The couplings $\bar{Q}_R B \mathcal{C}_L$ and $\bar{Q}_L C^\dagger \mathcal{C}_R$ may be excluded by the imposition of a discrete symmetry $Q \to -Q$, $\mathcal{C} \to \mathcal{C}$.)

Of particular importance is the vector mass matrix which determines the complexion of the gauge interactions. Except for the parts involving the singlets T and T' (whose presence necessitates the introduction of D) this matrix has been analysed in Ref.2. The contribution of D will cause some not very significant modifications in the masses of the charged vectors, but the neutral (diagonal) components will be affected more drastically. These are given by

$$\begin{aligned}
&\frac{g^2}{4}(3a_1^2 + a_4^2)(W_L - W_R)^2 + \frac{b_4^2}{4}\left(gW_R + f\sqrt{\frac{3}{2}}\, V_{15} + hT - h'T'\right)^2 \\
&+ \frac{c_4^2}{4}\left(gW_L + f\sqrt{\frac{3}{2}}\, V_{15} + hT - h'T'\right)^2 + \frac{c_1^2}{4}\left(-gW_L + f\left(V_3 + \frac{V_8}{\sqrt{3}} + \frac{V_{15}}{\sqrt{6}}\right) - hT + h'T'\right)^2 \\
&+ \frac{c_1^2}{4}\left(gW_L + f\left(-V_3 + \frac{V_8}{\sqrt{3}} + \frac{V_{15}}{\sqrt{6}}\right) - hT + h'T'\right)^2 + \frac{c_1^2}{4}\left(gW_L + f\left(-\frac{2V_8}{\sqrt{3}} + \frac{V_{15}}{\sqrt{6}}\right) - hT + h'T'\right)^2 \\
&+ \frac{d^2}{4}\left(f\sqrt{\frac{3}{2}}\, V_{15} + h'T'\right) + \frac{\mu^2}{2}(hT - h'T')^2 \;.
\end{aligned} \tag{5}$$

The last term is the only non-Higgs contribution consistent with both renormalizability and electromagnetic gauge invariance.

The photon is expressed by the exact formula

$$\frac{1}{e} A = \frac{1}{g} (W_L + W_R) + \frac{1}{f} \left\{ V_3 + \frac{1}{\sqrt{3}} V_8 - \sqrt{\frac{2}{3}} V_{15} \right\} + \frac{1}{h} T + \frac{1}{h'} T' \quad , \tag{6}$$

but the other seven states are thoroughly mixed and we shall attempt only a very approximate diagonalization (for a specially favourable sequence of parameters). We assume that g is small relative *) to f,h,h' and we shall neglect terms of order g/f, g/h and g/h' . Further, we assume that $h > \mu > d > c$ and neglect terms of order $(\mu/b)^2$, $(d/\mu)^2$, $(c/d)^2$. In this approximation one can treat the subsystems $\{W_L,W_R\}$, $\{V_3,V_8\}$ and $\{V_{15},T,T'\}$ independently. **) One finds

$$S_1 = \frac{f \sqrt{\frac{3}{2}}\ V_{15} + hT - h'T'}{\sqrt{\frac{3}{2} f^2 + h^2 + h'^2}} \quad , \quad S_2 = \frac{-(h^2 + h'^2)\ V_{15} + \sqrt{\frac{3}{2}}\ f(hT - h'T')}{\sqrt{(h^2 + h'^2)\ (\frac{3}{2} f^2 + h^2 + h'^2)}} \quad ,$$

$$S_3 = \frac{h'T + h\ T'}{\sqrt{h^2 + h'^2}} \quad , \tag{7}$$

with the respective masses

$$m(S_1) = \frac{1}{\sqrt{2}}\ b_4\ \sqrt{\frac{3}{2} f^2 + h^2 + h'^2} \quad , \quad m(S_2) = \sqrt{\frac{3}{2}}\ \mu \sqrt{\frac{h^2 + h'^2}{\frac{3}{2} f^2 + h^2 + h'^2}} \quad ,$$

$$m(S_3) = \frac{1}{\sqrt{2}}\ d\ \frac{hh'}{\sqrt{h^2 + h'^2}}$$

while the octet $V(8)$ has the mass fc_1 .

The static interaction between the PRE's mediated by V_{15}, T and T' is dominated by the S_3 pole whose contribution to the vector propagators is summarized by the matrix

$$\begin{pmatrix} (VV) & (VT) & (VT') \\ (TV) & (TT) & (TT') \\ (T'V) & (T'T) & (T'T') \end{pmatrix} \sim \frac{i}{k^2 - m(S_3)^2}\ \frac{1}{h^2 + h'^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & h'^2 & hh' \\ 0 & hh' & h^2 \end{pmatrix} . \tag{8}$$

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*) We are assuming that the two U(1)'s represent strong or medium strong interactions. This ensures that Q,$\mathcal{C}$ and $\mathcal{A}$ bind to form quarks and leptons. Thus $\frac{g^2}{4\pi} = 2\alpha < \frac{h^2}{4\pi} , \frac{h'^2}{4\pi} \leq \frac{f^2}{4\pi}$.

**) In Ref.1 the field V_{15} was denoted by S^0 .

Note that the inter-PRE forces have a range $m(S_3)^{-1} \sim 1/hd$, which is considerably shorter than the range, $1/fc_1$, of the strong inter $\mathcal{C}$ forces mediated by the colour octet of gluons $V(\underset{\sim}{8})$. Thus one expects quarks and leptons to be point-like (size $\approx m(S_3)^{-1}$). The important point is that <u>they are neutral with respect to both U(1) charges</u>. Thus for energies or momentum transfers less than their size $\left[\approx m^{-1}(S_3) \approx d^{-1} \left[\frac{h^2 h'^2}{2h^2 + 2h'^2} \right]^{-1/2} \right]$, quark-quark, lepton-lepton and quark-lepton scattering would be <u>insensitive</u> to T and T' forces. Knowing that leptons are point-like up to about 10^{-15} cm, we infer that $m(S_3) \gtrsim 100$ GeV.

The quarks interact strongly among themselves primarily through the exchange of the colour octet of gluons $V(\underset{\sim}{8})$. This provides the qqq and $q\bar{q}$ binding to form known baryons and mesons *) .

The existence of PRES inevitably implies a rich spectroscopy involving for example, $Q\bar{Q}$, $\mathcal{C}\bar{\mathcal{C}}$, $Q\bar{Q}\mathcal{C}\bar{\mathcal{C}}$, etc. composites in addition to $q\bar{q}$ composites.

The gauge theory presented so far conserves individual fermion numbers F_Q , $F_{\mathcal{C}}$ and $F_{\mathcal{A}}$ unless these numbers are broken spontaneously. This would imply the existence of three stable PRE's. Spontaneous symmetry breaking can lead to violation of these individual numbers F_Q, $F_{\mathcal{C}}$ and $F_{\mathcal{A}}$, conserving only their sum. Even this may ultimately be violated, if we extend the local symmetry exhibited in this paper; so that in the end only e^-, ν_μ , ν_e are

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*) There is the intriguing possibility that the known mesons $(\pi,\rho,\cdots)$ are composites of PRE-valency objects $(Q\bar{Q})$ rather than quark-anti-quark composites $\bar{q}q$. With the charge assignments of this note the $\pi^0 \to 2\gamma$ rate is the same as in the conventional colour model where π^0 is $\bar{q}q$ composite. The $\mathcal{C}\bar{\mathcal{C}}$ composites, held together by $V(\underset{\sim}{8})$ exchanges, may be the relatively lower lying J/ψ's . The decays of such $\mathcal{C}\bar{\mathcal{C}}$ composites to normal hadrons + one photon may be inhibited compared with radiative decays of normal hadrons if $h^2 \approx h'^2 \sim f^2/10$. This is due to the fact that one must create appropriate $Q\bar{Q}$ and $\mathcal{A}\bar{\mathcal{A}}$ pairs through the intermediacy of the relatively weaker T and T' interactions. Conceivably the narrow J/ψ (3.1) may correspond to the ground state $^3S_1$ $\mathcal{C}\bar{\mathcal{C}}$ rather than $\bar{q}q$ colour octet; ψ' (3.7) being its radial excitation. This may allow the ground state $^1S_0$ $(\mathcal{C}\bar{\mathcal{C}})$ to lie below 3.1 GeV and $\mathcal{C}$-even $(^3P_0, {}^3P_1, {}^3P_2)$ states to lie above the (3.1) state.

the three stable objects into which all particles decay *).

One important consequence of the PRE hypothesis is that quark decays (i.e. $q \to \ell + \ell + \bar{\ell}$ and $q \to \ell$ + mesons) induced via W-X mixing [4] proceed through bound state vertices. This alters the complexion of the graphs giving leptonic and semi-leptonic decays so that the semi-leptonic decays no longer represent the dominant decay modes of composite quarks. For quark searches this may be of crucial significance.

The above considerations have all been qualitative. The problem of computing bound states is of course non-trivial even when feasible. The hardest among these problems is the question of zero-mass leptonic composites, i.e neutrinos. While it is not impossible that such states could arise due to fortuitous relationships among the various masses and couplings in the Lagrangian, we do not feel that such an eventuality is plausible. Rather, we should like to view the neutrinos (like the photon) as special "composites" whose existence should be guaranteed by a symmetry principle. In the case of the photon, the relevant symmetry is of course gauge invariance. For the neutrino it may be possible to incorporate supersymmetry (whose spontaneous breakdown leads inevitably to the appearance of zero-mass spinors).

The eight (or nine) PRE's we have introduced in this paper represent eight (or nine) internal symmetry attributes. It is hard at present to conceive of a theory which uses fewer fundamental entities, unless some of the attributes disappear experimentally. The main point of this note, however, is that each fundamental attribute should be associated with one fundamental PRE-entity.

We thank Professor C.H. Woo for several helpful discussions on the problem of compositeness.

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*) It is conceivable that the $\bar{\mu}_e$-events seen at SPEAR (M. Perl, SLAC Conference) are due to production of PRE's, e.g. $\mathcal{C}_b^+ + \mathcal{C}_b^-$ production followed by their three-body decays, i.e. $\mathcal{C}_b^- \to \mathcal{C}_b^0 + e^- + \bar{\nu}_e$, brought about through W-X mixing (Ref.2).

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