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**INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS**

THE UNCONFINED UNSTABLE QUARK
(PREDICTIONS FROM A UNIFIED GAUGE THEORY
OF STRONG, WEAK AND ELECTROMAGNETIC INTERACTIONS)

Abdus Salam

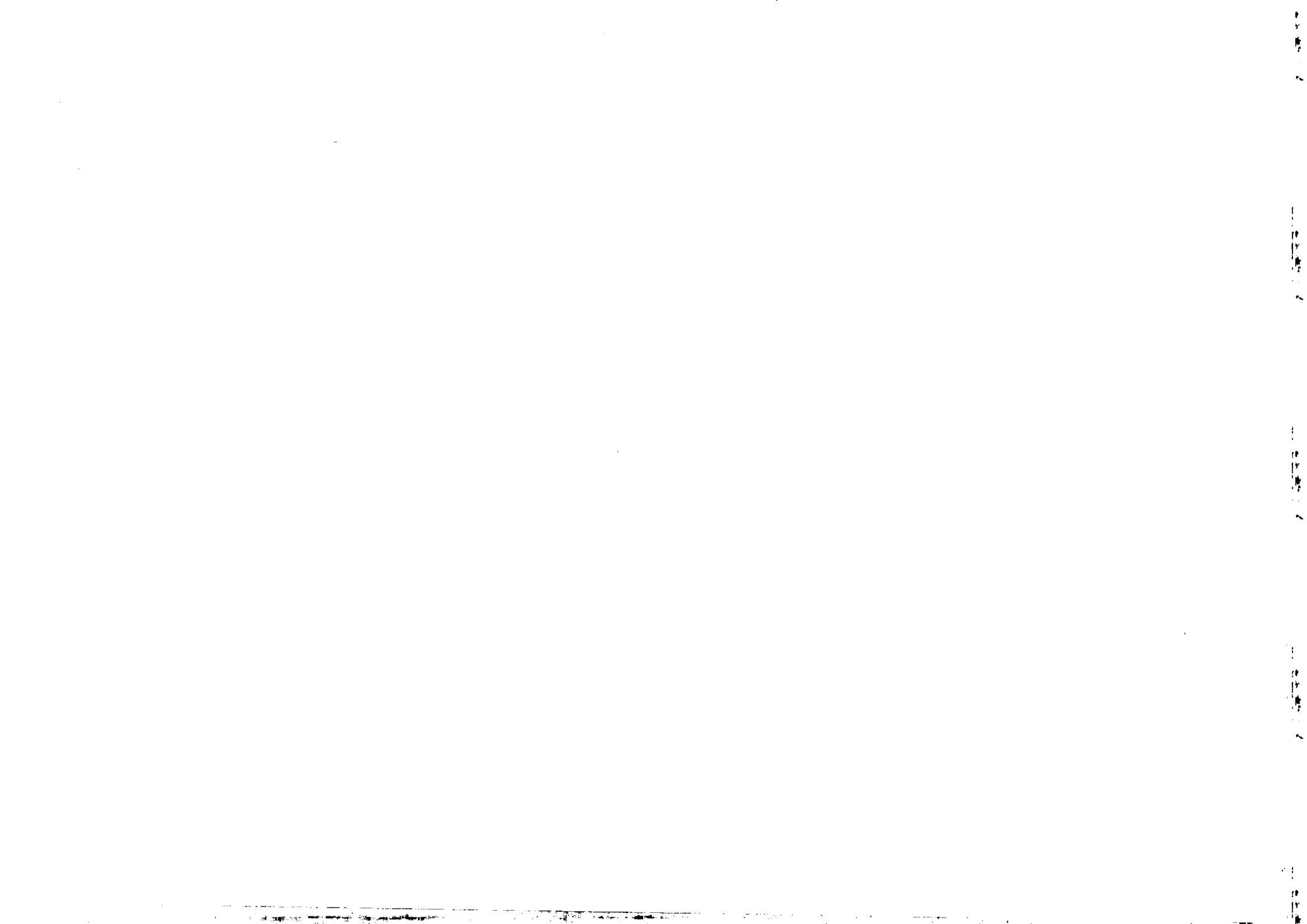


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THE UNCONFINED UNSTABLE QUARK
(PREDICTIONS FROM A UNIFIED GAUGE THEORY
OF STRONG, WEAK AND ELECTROMAGNETIC INTERACTIONS) *

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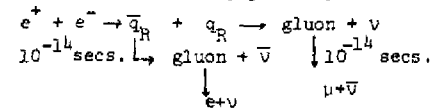
* Presented at CERN Colloquium, 28 February 1976.

ABSTRACT

Within the context of a unified gauge theory of integer-charge quarks and leptons, it is shown that quarks may decay purely leptonically as well as semi-leptonically with the following selection rules:

- 1) Yellow and blue quarks decay predominantly into mesons + neutrinos with lifetimes $\approx 10^{-11} - 10^{-12}$ secs. (for $m_q \approx 2$ GeV).
- 2) Red quark can decay leptonically or into mesons + neutrinos or mesons + charged leptons (e^-, μ^-). They are long-lived ($\approx 10^{-8}$ secs.) if no coloured gluon states exist with masses lower than red quarks.

3) If such gluons do exist, the lifetime of red quarks may be of the same order as that for yellow and blue quarks. In this event and if $m_q \leq 2$ GeV, SLAC (μe) events may possibly be interpreted as the chain decay



4) In lepto-production experiment, production of colour is suppressed to a 10-15% level in the present kinematic region, because of the gauge character of coloured gluons. There should be no such suppression in N-N production of colour.

(4) Introduce Higgs-Kibble spin-zero fields^{*} to give rise to the appropriate spontaneous symmetry breaking.

I. THE SIGNIFICANCE OF GAUGE THEORIES

During 1972 and 1973 a unified gauge theory of hadronic and leptonic interactions was proposed by Pati and myself¹⁾. The chief departure of this theory was the insistence that leptons and hadrons - sharing equally, as they do, forces of gravity, electromagnetism and weak interactions - do not represent radically different forms of matter. The theory predicted that baryons can decay into leptons and that beyond a certain (high) energy range, all their interactions will be similar. It is of interest to examine the status of this theory in the light of the recent experimental information from SLAC, DESY, Serpukhov, CERN and FNAL.

There is no question but that the chief quest of particle physics research is a deeper understanding of the concept of generalized "charge" - an understanding which should at least be as deep as that attained by Einstein for "gravitational charge". There have been two major steps towards this in our generation.

(1) The understanding of partial conservation of charge in terms of the phenomenon of spontaneous symmetry breaking or - as the condensed matter physicist would (perhaps more correctly) put it - in terms of the onset of ORDER.

(2) The removal of distinction between weak, electromagnetic and strong charges. This development started with the Gell-Mann-Nishijima formula and continued through current algebraic ideas.

Now both these developments find their most significant dynamical setting within unified gauge theories, and this is what makes these theories so significant.

II. THE GAUGE STRATEGY AND PREONS

The standard procedure in constructing a gauge model is the following:

- (1) Recognize a conserved (or partially conserved) set of charges and their symmetry algebra.
- (2) Fix on one (or more) basic Fermi multiplet exhibiting the appropriate symmetry.
- (3) Use the standard Yang-Mills techniques to obtain a unique interaction Lagrangian

$$L_{int} = e J_{\mu}^i A_{\mu}^i ;$$

J_{μ}^i are conserved currents constructed from the Fermi fields and the fields A_{μ}^i at this stage. L_{int}

In accordance with this strategy, let us consider how many conserved or partially-conserved charges we empirically recognize at present.

(a) First, there are the two lepton-numbers L_e and L_{μ} and baryon-number B . We assign $L_e = 1$ to ν_e and e^{-} , $L_{\mu} = 1$ to ν_{μ} and μ^{-} , and $B = 1$ to quarks ($B = 3$ for nucleons).

Define a fermion-number $F = L_e + L_{\mu} + B$; the quarks as well as leptons carry fermion-number $F = 1$.

(b) There appear to be at least four known flavour charges: I-spin up, down, strangeness and charm.

(c) At least three colour charges: RED, YELLOW, BLUE.

(d) If heavy leptons (and perhaps heavy quarks) exist, there may be a heaviness quantum number H .

I have not mentioned electric charge, since it is assumed to be made up of some of the charges listed above. The same may be true of some of the other charges listed. All in all, then it would seem that there are possibly of the order of eight or nine independent conserved (or partially-conserved) charges. The maximal symmetry group which one may gauge might therefore be the simple $U(8)$ or $U(9)$ - or, more accurately, distinguishing chirality, the groups $U_L(8) \times U_R(8)$ or $U_L(9) \times U_R(9)$.

Consider next the choice of the basic Fermi multiplet. The ideal choice would be a set of fermions, such that one fermion carries one fundamental charge. When quarks were first invented, they possessed precisely this property; each quark carried one flavour. With the invention of colour, the situation has changed; each quark carries two charges, flavour and colour (besides baryon-number) and this has led to an inflation in their numbers. For a fundamental theory of gauge interactions with eight or nine conserved charges, what we obviously need is eight or nine PRE-QUARKS or PREONS (fields) of which all quarks and all leptons may be made as composites²⁾.

^{*} Whereas group theory uniquely determines the pattern of vector mesons in a gauge theory, the pattern of spontaneous symmetry breaking and Higgs-Kibble particles is not unique, except in a supersymmetry. Since it is this pattern which ultimately determines the decays of particles in the theory - including the decays of quarks and gluons which we discuss in this note - a different set of Higgs-Kibble multiplets can affect the decay predictions. The only way to define the theory uniquely is through an experimental determination of the lower-lying Higgs-Kibble scalars. This is hard but worthwhile.

Clearly the manner in which PREONS are specified is the same as the specification of the details of the model. As an example of one choice of PREONS, consider $4 \times 3 = 12$ quarks (each carrying one of the four flavours and one of the three colours) plus the four leptons (ν_e , e^- , μ^- and ν_μ). One may consider these sixteen objects as composites of eight spin- $\frac{1}{2}$ PREONS, which are:

- (1) Four flavour PREONS \rightarrow which may be identified with the four leptons $L = \nu_e, e^-, \mu^-, \nu_\mu$.
- (2) Three colour PREONS $\rightarrow C = C_R^0, C_Y^-, C_B^-$.
- (3) One singlet PREON S^0 .

The twelve quarks are composites of $L\bar{C}S$. The economical concept of PREONS - all as elementary as leptons - is appealing and will become more so if more flavours are discovered. But perhaps the time (and the energy range) for PREONS to be discovered is not yet. *) As an interim we shall work with "composite" quarks and leptons in the context of an interim symmetry group $SU_L(4) \times SU_R(4) \times SU(4)$ (which is a subgroup of the PREON group $SU_L(8) \times SU_R(8)$). (Personally I believe that the "final" gauge theory, besides incorporating with some version of PREONS, will also be "supersymmetric". With such a theory the problem of Higgs-Kibble particles, their mutual couplings, as well as the basic theory of massless neutrinos and their (inevitable) mixing with baryonic quarks may be resolved in a fundamental manner.)

III. INTERIM GAUGE THEORY OF QUARKS AND LEPTONS

Assume that the fermionic multiplet is a 16-plet consisting of twelve quarks and four leptons:

$$F = \begin{pmatrix} F_R & F_Y & F_B & \nu_e \\ n_R & n_Y & n_B & e^- \\ \lambda_R & \lambda_Y & \lambda_B & \mu^- \\ c_R & c_Y & c_B & \nu_\mu \end{pmatrix}$$

The flavour quantum numbers extend along columns; the colour quantum numbers extend along the rows of this 4×4 matrix (we assign the leptons a fourth colour, lilac). There are two versions for electric charges of quarks:

*) If colour-preons carry fractional charge $-\frac{2}{3}$, we recover the fractionally charged quark model.

(A) Fractional-charge quarks

$$Q = \begin{pmatrix} \frac{2}{3} & \frac{2}{3} & \frac{2}{3} & 0 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & -1 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & -1 \\ \frac{2}{3} & \frac{2}{3} & \frac{2}{3} & 0 \end{pmatrix}$$

Note $\sum_{\text{quarks}} Q^2 = 10/3$ in this model.

(B) Integer-charge quarks

$$Q = \begin{pmatrix} \frac{2}{3} & \frac{2}{3} = 0 & \frac{2}{3} & \frac{1}{3} = 1 & \frac{2}{3} & \frac{1}{3} = 1 & 0 \\ \frac{1}{3} & \frac{2}{3} = -1 & \frac{1}{3} & \frac{1}{3} = 0 & \frac{1}{3} & \frac{1}{3} = 0 & -1 \\ \frac{1}{3} & \frac{2}{3} = -1 & \frac{1}{3} & \frac{1}{3} = 0 & \frac{1}{3} & \frac{1}{3} = 0 & -1 \\ \frac{2}{3} & \frac{2}{3} = 0 & \frac{2}{3} & \frac{1}{3} = 1 & \frac{2}{3} & \frac{1}{3} = 1 & 0 \end{pmatrix}$$

Here the charge operator is the sum of flavour charges + colour charges:

$Q =$ flavour charge Q_F (which like model (A) has the eigenvalues $\frac{2}{3}, \frac{1}{3}, \frac{1}{3}, \frac{2}{3}$)
+ colour charge Q_C which takes the values $(\frac{2}{3}, \frac{1}{3}, \frac{1}{3})$.

Note $\sum_{\text{quarks}} Q^2 = 6$ in this model.

Note also the important circumstance that red quarks carry the same net charges (0, -1, -1, 0) as leptons, while blue and yellow quarks exhibit a different sequence of charges (1, 0, 0, 1).

Since fractional charge quarks appear to be excluded by experiment, I shall be concerned mainly with integer-charge quark model (B) and shall try to show that the gauge theory based on these quarks and leptons is a

perfectly viable - and even an attractive - theory so far as any known experiments are concerned. Such quarks have simply not been looked for.

(1) Specifically we shall assume that such quarks exist and that they are not too massive. Though we have no theoretical reasons whatever for this, we shall suggest that m_q may be as low as 2 GeV. The grouping of quarks and leptons within the same fermionic multiplet will have the consequence that, dynamically, quark-lepton transitions will be possible. And if we permit a spontaneous violation of baryon-number B (and lepton-number L) such that fermion-number F (= B + L) is not violated ($\Delta F = 0$), a quark will decay into a lepton (+ mesons). This possible instability of quarks against decays into leptons, is the resolution of the integer-charge quark dilemma, if any.

(2) I shall show that spontaneous symmetry breaking, as implemented in the model, leads to the result that yellow and blue quarks decay predominantly into neutrinos + mesons but not electrons + mesons. This restriction does not hold for red quarks. It is conceivable (provided $m_q \lesssim 2$ GeV and provided certain other conditions (see Sec.VI) are satisfied) that SLAC (μe) events are due to production and subsequent decays of red quark-anti-quark pairs in $e^+ + e^-$ annihilation.

(3) A crucial consequence of strong gauging of integer-charge quarks is the existence of a gauge 1^- colour-gluon octet G(8) with masses of gluons possibly as low as 1.5 GeV (though a more likely mass value may be ≈ 4 GeV). At least one neutral member of this octet must be produced in $e^+ + e^-$ annihilation.

(4) Although this neutral member of G(8) mixes with the photon (which³⁾ therefore contains colour pieces), we show that the gauge character of the theory implies that the colour part of quark electric charge does not shine forth too brightly in electroproduction experiments. Thus sum rules based on SLAC and FNAL electroproduction structure functions at present accuracy do not distinguish between fractional and integer quark charge models. This suppression of colour in lepto-production experiments is not operative for colour production through N-N collisions where colour ought to manifest itself strongly.

IV. $SU_L(2) \times SU_R(2) \times SU_C(4)$ GAUGE GROUP AND THE DOGMA OF CONFINEMENT

Following standard practice, we gauge flavour charges for weak and electromagnetic interactions, the gauge group being $SU_L(2) \times SU_R(2)$ (of which the standard weak and electromagnetic $SU_L(2) \times U_R(1)$ is a subgroup). The coupling parameters are g_L and g_R with $\frac{g_L^2}{4\pi} = \frac{g_R^2}{4\pi} \approx \alpha$. Apart from the left-right symmetry of $SU_L(2)$ with $SU_R(2)$, so far as the gauge interaction is concerned, there is nothing particularly special about the gauges. We do not consider these further but turn to the more interesting gauging of the colour symmetry $SU_C(4)$.

There are fifteen 1^- colour gauge fields; consisting of an $SU_C(3)$ octet G(8), an $SU_C(3)$ singlet S^0 plus the $SU_C(3)$ triplet X^0, X^-, X^+ (together with its hermitian conjugate). G(8) couples quarks with quarks and mediates strong quark-quark forces (coupling parameter $\frac{f_{eff}^2}{4\pi} \approx \frac{1}{4} \sim 1$). The exotics X^0, X^-, X^+ couple red, yellow and blue quarks, respectively, with leptons, while the singlet S^0 couples quarks with quarks plus leptons with leptons. Since quark-lepton and lepton-lepton forces are weak at presently attained energies, it is clear that the $SU_C(4)$ symmetry must be broken spontaneously in such a manner that the exotic X's as well as S^0 are very massive.

To give masses to all the gauge fields ($W_L, W_R, G(8), X^0, X^-, X^+, S^0$) except the photon - as well as to respect flavour and colour SU(3)'s - we appear to need three Higgs-Kibble (4×4) multiplets, A, B and C, in the integer-quark-charge model, which give rise to the following sets of masses:

	Mass	Input
G(8)	1.5 - 6 GeV	strong q-q force
W_L^\pm	50 - 100 GeV	strength of (V-A) weak forces
W_R^\pm	> 300 GeV	strength of V+A weak forces
	(> 10^4 GeV in the model)	
S^0	$\approx 10^4$ GeV - 10^5 GeV	strength of I = 0 weak forces
X	$\approx 10^4$ GeV - 10^5 GeV	$K_L + \mu + e$ branching ratio $< 10^{-9}$.

Notice the semi-empirical hierarchy $1 : \alpha^{-1} : \alpha^{-2}$ between G(8): W_L^\pm ; and X masses. We do not know any deep reason for this.

³⁾ Since this is an interim gauge theory and we are gauging only a subgroup of the "final" simple symmetry group of charges (SU(8) or SU(9)), we do not insist on the effective coupling parameters $f^2/4\pi$ and $g^2/4\pi$ to be equal.

The mass matrix for the gauge mesons will induce the following three types of mixings, with mixing parameters completely fixed in terms of the input masses already introduced above.

$$(1) G^{\pm} \leftrightarrow W_L^{\pm} \text{ mixing } \approx \left(\frac{m_d}{m_W} \right)^2 \frac{g}{f} . \text{ As we shall see, this will be}$$

relevant to dimuon rate in $(\nu, \bar{\nu}) + N$ experiments.

(2) $W_L^{\pm} \leftrightarrow X^{\pm}$ mixing. This mixing and its magnitude will be relevant for quark decays into leptons (and also proton decays into leptons).

(3) W^0, S^0 and $U = G_3 + \frac{G_8}{\sqrt{3}}$ mixing to give the (massless) photon, which has the composition

$$\frac{1}{e} A = \frac{1}{g} (W_L^3 + W_R^3) + \frac{1}{\sqrt{3}} (U - \sqrt{\frac{2}{3}} S^0) .$$

So much for the integer-quark-charge model.

At this point one should make a comparison with the colour gauge structure in the fractional quark-charge model. So far as gauging of flavour charges and the need for a spontaneous symmetry breaking mechanism to provide masses for W_L^{\pm} and W_R^{\pm} weak mesons is concerned, both models agree. When it comes to colour symmetry, the development of the fractional charge model has followed a totally different path. The protagonists of this model - and this includes the vast majority of the theoretical community - impressed by the non-existence of colour-carrying fractional charge quarks, have sought to resolve the quark dilemma by postulating the Dogma of Colour Confinement. The Dogma states that strong quark dynamics - chromodynamics (QCD) of the colour group $SU_c(3)$ - is such that only colour singlets can exist as physical entities. All other colour states - and this includes quarks as well as $G(8)$ colour gluons - are exactly and inexorably confined. *)

*) Some physicists have suggested that colour confinement is analogous to "confinement" of magnetic charge in Maxwell-Faraday electrodynamics. This is incorrect. Unlike colour charge, non-zero magnetic charge is never introduced as a source in field equations of conventional electrodynamics. The remarkable result of QED field equations - the understanding of magnetic dipole phenomena in terms of moving electric charges - would have an analogy in colour dynamics (quantum chromodynamics, QCD) if one could explain all colour phenomena in terms of flavour charges and never have to introduce non-zero colour charges.

The great merit of the Exact Confinement Dogma is the end it would make to the elementarity concept; perfectly confined quarks are invisible; one would not have to worry about any PRE-QUARKS. Elementary Particle Physics would therefore end with quarks so far as hadronic matter is concerned. For leptons, since we are presumably dealing with visible elementary entities (neutrinos, electrons), the end of the chain is sharply different and perhaps more standard.

Now, three types of attempts have been made to ensure colour confinement.

(1) Gravitational confinement

There is no question but that with suitable boundary conditions and with suitable conditions of matter density obtaining, classical spin-2 Einstein tensor fields do confine. Thus hadrons could be viewed as f-gravity black holes if we postulate that f mesons satisfy Einstein's field equations (in the zero mass limit, and provided such a limit is soft). The MIT confining bags may perhaps be viewed as scalar-gravity bags (with a cosmological term). Apart from Hawking's recent results concerning instability of small black holes (black holes of mass $< 10^{-5}$ gms are unstable for f gravity) the major difficulty with this type of confinement is that it is all-embracing and too non-selective; both colour and flavour are likely to be confined.

(2) Quark confinement as a critical phenomenon

Wilson and, following him, Susskind, Kogut and others have attempted to confine colour in a lattice version of (non-Lorentz invariant) gauge theories. The hope is that when the space-time lattice constant goes to zero and covariance is restored, confinement will persist. Even if this fine attempt succeeds, one's experience with critical phenomena is that there are always external agencies capable of restoring the system to an unconfined phase. Thus, confinement through a critical mechanism is likely to be partial and not exact.

What is ambitiously being attempted in confined versions of chromodynamics is to introduce non-zero colour charges in the field equations but at the same time ensure colour confinement through boundary conditions. This is very different from the case of the Maxwell-Paraday electro-dynamical theory where all solutions of field equations exhibit non-appearance of magnetic charge - and that simply because no such charge is ever introduced into the field equations.

(3) Infra-red slavery

The most widely held belief has been that exact confinement would result from the highly singular infra-red behaviour of massless Yang-Mills gluons in an exactly-conserving $SU_c(3)$ gauge theory. In a fractionally charged quark model, such gluons are electrically neutral and would remain massless if $SU_c(3)$ is an exact symmetry of nature. *) This phenomenon has been called infra-red slavery. A second advantage of such an exactly conserved $SU_c(3)$ could be the possibility of securing asymptotic freedom for the theory - i.e. the possibility that $f_{eff}^2/4\pi$ decreases as energy increases - justifying the use of perturbation theory in strong interaction physics.

Now, so far as asymptotic freedom is concerned, it must be stressed that exact colour symmetry is a sufficient condition for this, but by no means necessary. It is a commonly held - but a fallacious - belief that massiveness of vector mesons and Higgs-Kibble scalars always spoils asymptotic freedom. The little-known work of Chang ⁴⁾, Fradkin ⁵⁾ and others has conclusively shown that a spontaneously broken $SU_c(3)$ can also be asymptotically free, provided the Higgs-Kibble fields belong to special classes of representations and there are relations among their couplings (supersymmetric theories provide examples of this).

Regarding infra-red slavery, an important result has recently been provided by Appelquist, Carazzone, Kluberg-Stern and Roth. These authors analyse production of massive fermions by an external current in a massless Yang-Mills theory for infra-red singularities. They prove that to the lowest non-trivial order there are no infra-red singularities when transition probabilities are computed. They conjecture that their results hold to all finite orders. There is, therefore, no special piling up of Yang-Mills infra-red singularities, at least in the colour-emitting process they consider.

An objection has been raised to the work of these authors: could it be that if the perturbation series for an infra-red amplitude was summed first (with an infra-red cut-off imposed) and the cut-off removed after summing the perturbation series, the infra-red singularities would pile up, instead of cancelling out? And then if these singularities are taken seriously, transition amplitudes involving colour non-singlets may go to zero (similar to the setting of $z = 0$ for the ultraviolet singular case). This of course these authors have not checked, for one does not know how to sum reliably the perturbation series in a field theory. But one must make one point strongly which results from the work of Appelquist et al. Their result is that Yang-Mills theories behave in

*) Though Higgs-Kibble scalars can be found, even in this model, which could make the gluons massive.

exactly the same manner as electrodynamics so far as the infra-red behaviour of the matrix elements they consider is concerned. Nothing is singular in either theory up to a given order of computation and no matrix elements vanish. To a simple-minded physicist the moral is clear; either both Yang-Mills and electrodynamics confine or both do not. All in all, it seems no longer plausible that the infra-red slavery hypothesis can be relied upon to produce exact confinement, for all physical processes involving colour.

But what about partial confinement? This is the hypothesis that quarks and gluons - partons - while fairly massive and thus hard to produce as physical particles, behave as if they were relatively light - and even free - inside colour-singlet hadrons. This hypothesis - also part of the theory of the SLAC bag - I find perfectly plausible. The first person who recognized partial confinement was Archimedes - relatively lighter and freer *) so long as he remained inside his bath; grosser and heavier when he left it. Perhaps in his honour we should call partial confinement, the "Archimedes effect". Clearly partial confinement does not require massless gluons $G(8)$ nor exact $SU_c(3)$.

To conclude: If fractionally charged quarks are not found empirically the other alternative - of integer-charge quarks - is perfectly viable (as I shall show) and provides a complete and (so far as present experiments are concerned) an unobjectionable model. It should be discarded only after experiments fail to show (short-lived) integer-charge quarks and not because we may harbour theoretical prejudices based on a priori confinement ideas, which are yet far from definitive development. I would go even further: Even if the most elegant possible theory could be constructed to confine quarks, the question whether they are confined or not is still an open experimental question and can only be settled empirically.

*) If Archimedes was no denser than the salt water in his bath, and if salt water of the Ionian sea were non-viscous, Archimedes would have been as free as a parton swimming in the quark-gluon sea inside hadrons. As emphasised by the proposers of the SLAC bag and by T.D. Lee, partial confinement is accomplished most simply by a scalar field interacting with partons and gluons and exhibiting a superfluid phase. It would seem that the origin of the peculiar parton dynamics (Archimedes effect) lies as much in scalar (or spin 2 tensor) meson exchanges as in spin 1 meson exchanges.

If partons are (predominantly) quarks, there is one parton sum rule from lepto-production experiments, which is alleged to show that quark charges must be flavour-charges and fractional. We wish to examine this sum rule and show that in a gauge theory this particular sum rule does not provide any quantitative distinction between the fractional and integer-charge models. But before we do this let us consider colour gluons.

5.1 Where are the colour gluons?

As stated in the previous section, the photon in the integer-charge model contains flavour as well as colour pieces; ignoring the very massive S^0 particle, the photon's composition is of the form:

$$\frac{1}{e} A = \frac{1}{g} W + \frac{1}{f} U \quad U^0 = \left[G_3 + \frac{G_8}{\sqrt{3}} \right]$$

Before we discuss the role of the colour piece U in electroproduction, we must consider the actual production of the $1^- U^0$ gluon in $e^+ + e^-$ annihilation experiments at Frascati, DESY and SLAC. Which one, if any, of the various J/ψ or other $e^+ + e^-$ structures represents the coloured gluon U^0 ?

To answer, consider the three possibilities for the J/ψ objects permitted in the type of gauge models we are considering and which contain both charm and colour.

(1) Fractionally charged model

Charm excited but colour completely confined. Assuming the ratio

$$R = \frac{e^+ + e^- \rightarrow \text{hadrons}}{\mu^+ + \mu^-} \text{ equals } \sum_{\text{quarks}} Q^2 \text{ (as in the naive parton model),}$$

we find $R = 10/3$ for fractional charges, contrary to the experimental value ≈ 5.5 for the region above 4.5 GeV. But leaving aside this difficulty, the popular explanation of all $1^- J/\psi$ particles as charm-anti-charm composites encounters the well-known problem of explaining the narrowness of ψ and ψ' widths. The standard way to resolve this difficulty is to rely on HAIR-PIN ALGEBRA embodied in the form of a theoretically somewhat mysterious Zweig suppression rule. As is well known, such a rule is incompatible with unitarity. Even ignoring this, one finds that there really are two rules: one, the Zweig rule which operates, for example, for ϕ decay, and second, the super-Zweig rule, operative for J/ψ particles. The super-Zweig rule must find an extra suppression factor of $1/50$ or so from energy denominators, or a unitarity "correction" over and above the normal Zweig rule. The charm-anti-charm model for ψ, ψ' is not altogether without its difficulties.

(2) Second possibility

Colour excited but not charm. This is the alternative accepted by Matthews, Feldman, Stech, Bars, Peccei and Yamaguchi and others. Here

$$R = \sum_{\substack{\text{Han-Nambu} \\ \text{charmless quarks}}} Q^2 = 4,$$

slightly nearer the empirical value than the first alternative. This model predicts five coloured $1^- q\bar{q}$ composites* and this in fact is at present the number of J/ψ structures between 3.1 and 5 GeV.

This is nice. However, the problem of ψ, ψ' width is still acute. This is because, even though all decays go via the virtual (or real) photon and a factor α may be found from this mechanism, a factor $\approx \frac{1}{50} \sim \frac{1}{100}$ is still missing if we are to understand the narrow J and ψ 's as colour composites. In other words, the same suppression factor which for the first alternative was needed to diminish Zweig to super-Zweig is needed here beyond the factor α already in the model. Now both (1) and (2) above may be extreme views; there is a third possible alternative.

(3) The third alternative

BOTH CHARM and COLOUR EXCITED in the same energy region. Since

$$\sum_{\text{all quarks}} Q^2 = 6,$$

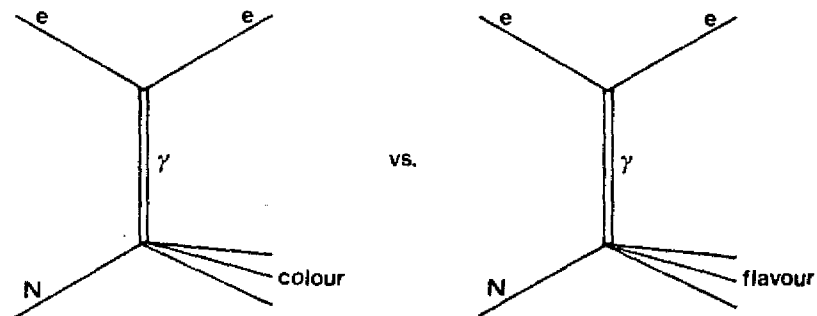
a naive identification of this with

$$R = \frac{e^+ + e^- \rightarrow \text{hadrons}}{\mu^+ + \mu^-}$$

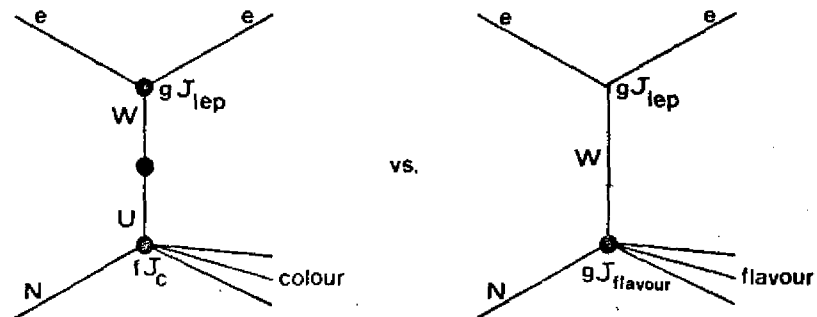
would appear to accord better with the experimental value of R (see later, this section, for a more correct identification). This alternative would predict three more structures besides the five already seen, but would cast

* Here $SU_c(3)$ breaks into $SU_c(2) \times U_c(1)$. This feature is possible to incorporate by a rather simple variant of Higgs-Kibble scalars in the model of this paper.

no new light on the dilemma of narrow J/ψ and ψ' widths. However, it permits us to take the view that even if most of the SLAC structures are charm-anti-charm composites, the coloured U^0 gluon (a few MeV wide) may lie among the tangled set of resonances around the 4.1 GeV region. In this section I shall take this view; later we shall examine whether U^0 may not in fact lie in the Frascati region - between 1 and 2 GeV in mass.



i.e.



i.e. the propagators $fg \langle WU \rangle$

vs.

$g^2 \langle WW \rangle$

assuming that the dynamical factors $\langle N | J_{\text{colour}} | \text{colour} \rangle$ and $\langle N | J_{\text{flavour}} | \text{flavour} \rangle$ are identical.

5.2 Colour suppression theorem for lepto-production

We now turn to the parton model sum rules for lepto-production. Roy and Rajakesran and Pati and I³⁾ independently proved the following theorem during the summer of last year.

Theorem

On account of the gauge nature of $G(8)$, there is a damping factor $\left(\frac{m_U^2}{|q^2| + m_U^2} \right)^2$ which (1) depresses colour contribution to SLAC and FNAL electro-production, as well as colour contribution to neutrino production, and (2) causes $\frac{\sigma_L}{\sigma_T} (\neq 0)$ in electroproduction to scale in x , when $G(8)$ vector gluon contribution is taken into account. As a consequence of this suppression, colour effects will not show themselves in present electroproduction experiments except, at most, at 15% level.

Proof

The mechanism of colour suppression is very easy to comprehend. It comes about basically because leptons are $SU_c(3)$ singlets. Write the gauge Lagrangian $L_{\text{int}} = g W J_W + f G(8) J_{\text{colour}}$, where the photon is $\frac{1}{e} A = \frac{1}{g} W + \frac{1}{f} U^0 \left(\frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{f^2}; \frac{g}{f} \approx \frac{1}{5} \approx \frac{1}{10} \right)$ and $J_W = J_{\text{flavour}} + J_{\text{leptons}}$. We want to compare, in electroproduction,

Now consider what the propagator factors $\langle WU \rangle$ and $\langle WW \rangle$ are. Write $\tan\theta = g/f \approx 1/10$. The two eigenstates for the W,U system are:

$$\begin{aligned} A &= \cos\theta W + \sin\theta U, \\ \tilde{U} &= -\sin\theta W + \cos\theta U. \end{aligned}$$

Since A and \tilde{U} are eigenstates,

$$\langle AA \rangle = \frac{1}{q^2}, \quad \langle \tilde{U}\tilde{U} \rangle = \frac{1}{q^2 - m_U^2}.$$

Hence

$$\langle WW \rangle = \frac{\cos^2\theta}{q^2} + \frac{\sin^2\theta}{q^2 - m_U^2},$$

$$\langle WU \rangle = \sin\theta \cos\theta \left(\frac{1}{q^2} - \frac{1}{q^2 - m_U^2} \right)$$

$$\langle UU \rangle = \frac{\sin^2\theta}{q^2} + \frac{\cos^2\theta}{q^2 - m_U^2}.$$

Clearly the amplitude

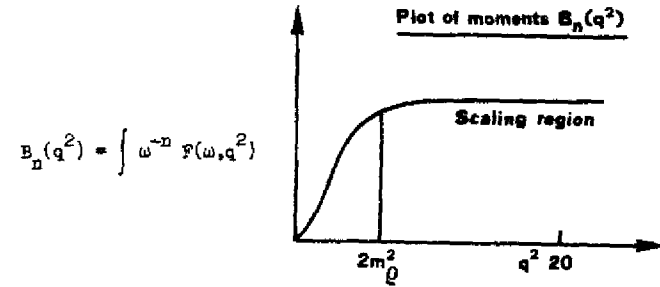
$$\begin{aligned} \frac{e + N \rightarrow \text{colour}}{e + N \rightarrow \text{flavour}} &= \frac{f}{g} \frac{\langle WU \rangle}{\langle WW \rangle} \frac{(N|J_{\text{colour}}|\text{colour})}{(N|J_{\text{flavour}}|\text{flavour})} \\ &\approx \left(\frac{1}{q^2} - \frac{1}{q^2 - m_U^2} \right) \frac{1}{q^2} \times \text{dynamical factor.} \end{aligned}$$

Thus the colour amplitude is damped by the factor $\frac{m_U^2}{q^2 - m_U^2}$. Quantitatively, therefore, $i = 1, 2, 3$

$$F_i(q^2, \nu) = F_i^{\text{flavour}}(q^2, \nu) + \left(\frac{m_U^2}{|q^2| + m_U^2} \right)^2 F_i^{\text{colour}}(q^2, \nu).$$

(for electroproduction $q^2 < 0$), and there is implied a colour threshold factor below which $F_i^{\text{colour}} \equiv 0$. Before we consider quantitative estimates, let us take note of one other (dynamical) source of colour damping. As we all know, $F_i(q^2, \nu)$'s scale, i.e. they are functions

of one variable $x = \frac{q^2}{2M_V^2}$. However, this scaling, so far as F_i^{flavour} are concerned, does not set in fully till q^2 empirically reaches the value $2m_p^2$.



Scaling implies $B_n(q^2) = B_n(\infty)$.

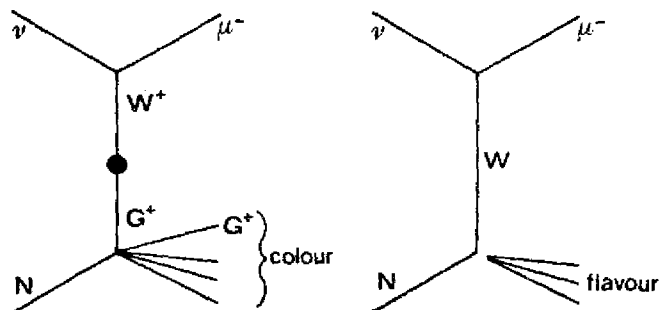
We shall assume that a similar dynamical effect exists for the approach to scaling so far as F_i^{colour} is concerned, except that q^2 would have to reach the characteristic colour mass $2m_V^2$ (rather than characteristic flavour mass $2m_p^2$) before full scaling is operative. This (un-understood) dynamical effect empirically provides another suppression source for colour (and flavour in the appropriate region of q^2). Thus, finally, we expect

$$\begin{aligned} \frac{\text{colour}}{\text{flavour}} &\approx \left| \frac{m_U^2}{|q^2| + m_U^2} \right|^2 \times \text{dynamical approach factor to scaling} \approx \frac{q^2}{2m_U^2} \\ &\quad \text{for } 2m_p^2 < q^2 < 2m_U^2 \\ &\approx \left| \frac{m_U^2}{|q^2| + m_U^2} \right|^2 \times 1 \text{ when } q^2, M_V > 2m_U^2 \text{ and } M^2 + 2M_V - q^2 > \text{colour threshold.} \end{aligned}$$

The two regions for q^2 essentially span SLAC and FNAL kinematic regions. Substituting numbers, it is easy to verify that with $m_U \sim 4$ GeV, the suppression factors for colour are $\sim \frac{1}{8} - \frac{1}{10}$ for both SLAC and FNAL. The colour/flavour contribution never exceeds 10-15% at most.

5.3 Colour suppression for neutrino-production

The same damping factor can be shown to be operative for colour production by neutrinos. As stated earlier, the charged gluons G_{\pm}^{\pm} and G_{\pm}^{\pm} mix with W^{\pm} , the mixing terms being given by $\sin(\theta+\phi) \left(\frac{m_G}{m_W}\right)^2 g/f$ and $\cos(\theta+\phi) \left(\frac{m_G}{m_W}\right)^2 g/f$ (θ and ϕ are (u,λ) and (p,c) mixing angles respectively ($\theta_{\text{Cabibbo}} = \theta - \phi$)). The neutrino production of colour then goes through the diagram



This must be compared with the flavour producing diagram and once again one can demonstrate the appearance of the damping factor in amplitude,

$$\frac{m_G^2}{|q^2| + m_G^2}$$

5.4 The quark charge sum rule

We now turn to the sum rule (proposed by Llewellyn-Smith and others) which is supposed to provide evidence for fractional quark charges. Consider

$$\frac{4G_F^2 M E_\nu}{2\pi(\sigma_{\nu^+} + \sigma_{\nu^-})} \int F_2^{YK} dx = r$$

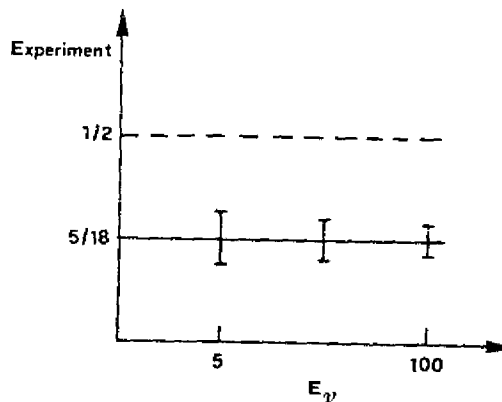
Neglecting gluon contribution from the parton model, this equals

$$r = \frac{\langle Q_{fla}^2 \rangle_{eN} + \langle Q_{col}^2 \rangle_{eN}}{\langle Q_{fla}^2 \rangle_{\nu N} + \langle Q_{col}^2 \rangle_{\nu N}}$$

For the fractional-charge model, the right-hand side equals $5/18 = 0.28$. For the integer-charge model, without any suppression factor for colour, the right-hand side equals $1/2$. With colour suppression, as discussed above, the right-hand side should read:

$$r = \frac{\langle Q_{fla}^2 \rangle_{eN} + \langle \epsilon \rangle \langle Q_{col}^2 \rangle_{eN}}{\langle Q_{fla}^2 \rangle_{\nu N} + \langle \epsilon \rangle \langle Q_{col}^2 \rangle_{\nu N}}$$

where $\epsilon \sim \frac{1}{9} - \frac{1}{10}$. Thus, with this suppression, the expectation from the integer-charge quark model is $0.28 + 0.03$. The experimental evaluation of the left-hand side simply cannot distinguish between the two cases.



5.5 The gluon contribution : structure functions

The gauge character of $G(8)$ gluons has an important bearing on the gluon contribution to the structure functions. Bell, Llewellyn-Smith and others have shown that in a gauge theory the behaviour of high energy, high momentum transfer form-factors for spin-one gluons is similar to the behaviour for spin- $\frac{1}{2}$ partons (as it should be in the context of a renormalizable field theory). This is very different from the situation for non-gauge massive spin-one particles. For example, if $G(8)$ were not gauge particles, their contribution (as partons) would give a q^2/m^2 non-scaling power violation to Bjorken behaviour for F_1 and $\frac{q^2}{m^2}$, and $\left(\frac{q^2}{m^2}\right)^2$ in F_2 . The extra factor $\left|\frac{m_U^2}{q^2 - m_U^2}\right|^2$ helps in restoring scaling behaviour to both F_1 and F_2 when $|q^2| \rightarrow \infty$. More specifically,

$$F_1^{\text{above colour threshold}} = F_1^{\text{below colour threshold}}$$

$$q^2 \rightarrow \infty$$

while

$$F_2^{eN} = F_2^{\text{flavour}} + \left(\frac{m_U^2}{|q^2| + m_U^2} \right)^2 \left[\frac{2x}{3} \sum (q(x) + \bar{q}(x)) \right. \\ \left. + xG(x) \left[4 + \frac{1}{3} \frac{|q^2|}{m_U^2} + \frac{1}{3} \left| \frac{q^2}{m_U^2} \right|^2 \right] \right]$$

where $G(x)$ is the gluon form factor. The experimental quantity which manifests the effect of $G(x)$ most clearly is the ratio

$$\frac{\sigma_L}{\sigma_T} = \frac{F_2^{eP} - 2x F_1^{eP}}{2x F_1^{eP}} \xrightarrow{|q^2| \rightarrow \infty} \frac{\frac{1}{3} x G(x)}{\sum x (q(x) + \bar{q}(x)) C_{fla}}$$

Thus $\frac{\sigma_L}{\sigma_T} \neq 0$ asymptotically and it scales. (Apparently there are recent experimental indications that indeed $\frac{\sigma_L}{\sigma_T}$ does show this behaviour.)

Note that $G(x)$ contributes asymptotically to $\frac{d^2 \sigma_{\nu N}}{dx dy}$ and $\frac{d^2 \sigma_{\nu N}}{dx dy}$ a term $\frac{MG_F^2}{\pi} (1-y) \frac{x}{2} G(x)$. This linearly dependent $(1-y)$ contribution may be relevant for high y , low x anomaly.

It is worth remarking that the factor $\frac{m_U^2}{q^2 - m_U^2}$ acts, not as

damping, but as an enhancing factor for time-like momenta $q^2 > 0$ in the region $q^2 < 2m_U^2$. This is the situation for $e^+ + e^- \rightarrow \text{hadrons}$. We thus expect $R = \frac{e^+ + e^- \rightarrow \text{hadrons}}{\nu^+ + \nu^-}$ to show a complicated behaviour with an enhancement followed by a damping, straddling the region $\sqrt{2} m_U$. In addition there is the expected gluon contribution; so that altogether

$$R = R_{\text{flavour}} + \left| \frac{m_U^2}{q^2 - m_U^2} \right|^2 \left(R_{\text{colour}}(\text{quarks}) + \frac{1}{8} \left(1 - \frac{4m_U^2}{q^2} \right)^{3/2} \left[1 + \frac{20q^2}{m_U^2} + \frac{4}{m_U^2} \right] \right)$$

Note also that for $q^2 = 2m_U^2$

$$R = R_{\text{flavour}} + R_{\text{colour}}(\text{quarks}) = 6$$

For $q^2 \rightarrow \infty$ (barring effects of anomalous dimensions in the propagators for photons and gluons), $R \rightarrow R_{\text{flavour}} + \frac{1}{8}$, where $\frac{1}{8}$ is the asymptotic gluon contribution.

To summarize, an important consequence of gauge aspects of coloured vector gluons is the theorem that in lepto-production colour does not shine too brightly asymptotically but is not invisible - showing itself most clearly through the gluons.

VI. GLUON AND QUARK DECAYS

6.1 Free gluon decays

The mixing of $G_\rho^\pm, G_{K^*}^\pm$ with W^\pm induces decays of free charged gluons:

- + $e\nu, \mu\nu$.
- + $\pi\pi, K\bar{K}, 3\pi$,
- + $\pi\pi e\nu, K\bar{K} e\nu, \eta e\nu$.
- + $e\nu\pi, K e\nu$.

But not

The semi-leptonic decays with one pion, one kaon and one η will not occur (except in a higher order) since $G(\delta)$'s are flavour singlets. This contrasts with flavoured objects like D, F particle decays where such decays may be more likely. One can estimate that $G_\rho^\pm + \frac{m_U e\nu}{ev} \approx \frac{1}{30} - \frac{1}{10}$. Also

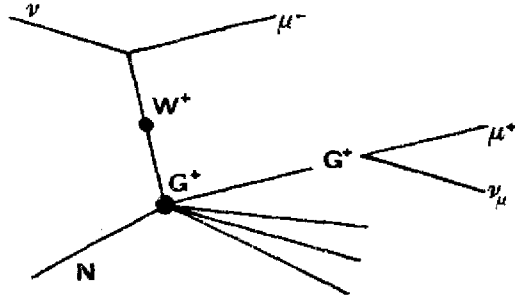
$$G \rightarrow \begin{matrix} \text{leptonic} \\ \text{all} \end{matrix} \approx \begin{matrix} 15 - 20\% \text{ if } m_G \gg 3 \text{ GeV} \\ 20 - 25\% \text{ if } m_G \approx 1.5 \text{ GeV} \end{matrix}$$

and

$$\tau(G_\rho) \approx \begin{matrix} 2 \times 10^{-14} & m_G \approx 1.5 \text{ GeV} \\ 5 \times 10^{-16} & m_G \approx 3 \text{ GeV} \\ 10^{-16} & m_G \approx 4.1 \text{ GeV} \end{matrix}$$

6.2 Dimuons

G-W mixing diagrams will give rise to dimuons:



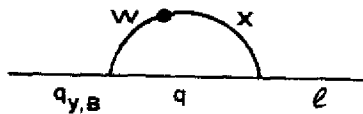
Notice that there is no $\sin^2 \theta_c$ factor, though there is the kinematic damping factor mentioned earlier in Sec.V. The net effect is that dimuon rate is of the same order of magnitude as the rate from charm production - which of course is additionally present in the model. Once again we stress that for production and decays of charged G's it is $K\bar{K}$ pairs (and not single K's) which are likely to accompany dimuons.

6.3 Quark decays

$W^- - X^-$ and $W^- - X'^-$ mixing is the mechanism responsible for quark-lepton transitions with $\Delta F = 0$, $\Delta B = -\Delta L$. (An important characteristic of this model is that there is no direct $X^0 - W^0$ mixing.)⁶⁾

Yellow and blue quarks

The basic diagram for decays of yellow and blue quarks is as shown.



The important point is that this diagram is finite. It gives rise to an effective Lagrangian: *)

$$\mathcal{L}_{eff} = \bar{q}_{Y,B} (1 + \gamma_5) \lambda \left\{ \frac{m_q}{8\pi m_X} c_4 \not{e} \not{q} \text{ for } \frac{m_X^2}{m_W^2} \right\}$$

*) It is possible to arrange the Higgs-Kibble potential so that $c_4 = 0$ in the tree approximation. In this case, for the basic model, the quarks, or rather the lightest among the quarks is stable. Assume this is p_R^0 . Then other quarks decay as follows:

$$q_{Y,B} \rightarrow p_R^0 + (\text{virtual or real}) G + \nu, \pi\pi, \text{ etc.}$$

$$q_R \rightarrow p_R^0 + (\text{virtual}) W + \nu, \pi\pi, \text{ etc.}$$

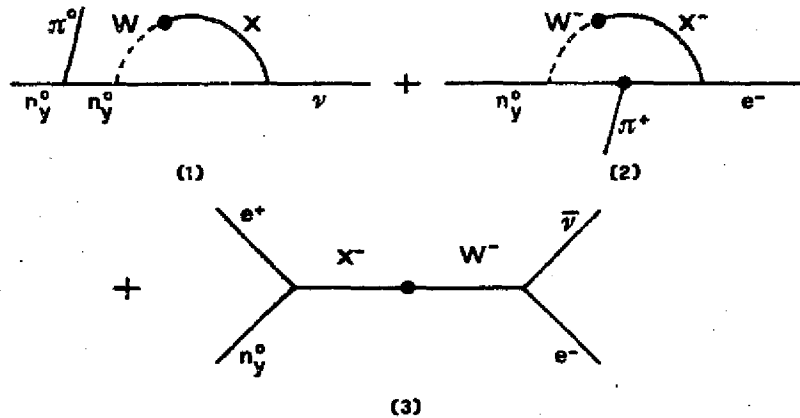
There is, then, the unattractive possibility of a quantity of p_R^0 matter being present in the Universe.

Now even though the potential may be arranged such that $c_4 = 0$ for the minimum in the tree approximation, this may not be a stable situation when radiative corrections are taken into account. To complete the list of possibilities, it is even conceivable that (1) such radiative corrections, or (2) spontaneous symmetry breaking in a parity-conserving supersymmetric theory (where some of the multiplets must contain $F = 2$ scalars for the sake of parity conservation (see Abdus Salam and J. Strathdee, Nucl. Phys. B97, 293 (1975)) or (3) spontaneous symmetry breaking in theories where fundamental fermionic multiplets contain both particles and antiparticles, may induce $|\Delta F| = |\Delta B| = 2$, $\Delta L = 0$ transitions (e.g. J.C. Pati, Abdus Salam and J. Strathdee, Nuovo Cimento 26, 72 (1975)). Thus

$q \rightarrow \text{nucleon} \begin{Bmatrix} \Delta F = 2 \\ \Delta B = 2 \end{Bmatrix}$ could also be a theoretically possible transition to resolve the quark dilemma as suggested by Nambu (for a discussion see J.C. Pati, S. Sakakibara and Abdus Salam, Trieste preprint, in preparation).

The factor in the bracket is of order $\approx 10^{-9} m_q$ with the mass of X adjusted from $K \rightarrow e + \mu$ rate.

We now show that the predominant decay of yellow and blue quarks^{*)} is into neutrinos (and not electrons) + mesons. To see this, consider the relevant decay diagrams (for example for n_y^0) in detail



All three diagrams are finite, but while the first is inversely proportional to the square of one large mass, the other two are inversely proportional to a product of (squares of) two large masses. (The pion is a composite particle in our model with a form factor $\propto 1/q^2$.) Thus the first diagram dominates over the other two. The expected decays of yellow and blue quarks are:

$$\begin{aligned}
 P_{Y,B}^+ &\rightarrow \nu_e + \text{pions}, \quad \nu_\mu + K^0 + \text{pions}, \\
 n_{Y,B}^0 &\rightarrow \nu_e + \text{pions}, \quad \nu_\mu + K^0 + \text{pions}, \\
 \lambda_{Y,B}^0 &\rightarrow \nu_\mu + \eta, \quad \nu_e + \bar{K}^0 + \text{pions}, \\
 C_{Y,B}^+ &\rightarrow P_{Y,B}^+ + \pi^0, \quad \lambda_{Y,B}^0 + \pi^+, \\
 &\rightarrow \nu_e + D^+, \quad \nu_\mu + F^+
 \end{aligned}$$

^{*)} In all these calculations, possible contributions from (intermediate) Higgs-Kibble particles have been neglected and only decays involving gauge mesons have been included. These Higgs-Kibble contributions are model dependent. Their inclusion affects the ratios of leptonic decay rates versus semileptonic decays of quarks. Some simple models will be considered elsewhere.

(assuming that D and F mesons are lighter than $C_{Y,B}^+$). Note the strangeness selection rule among the decays (muon is strange and ν_μ charmed).^{*)} For $m_q \sim 2 \text{ GeV}$, we obtain $\tau_{Y,B} \sim 10^{-11}$ to 10^{-12} secs.

To summarize, for yellow and blue quarks, firstly the purely leptonic mode is suppressed compared with semi-leptonic, and secondly yellow and blue quarks decay predominantly into neutrinos + mesons and not electrons (or muons) plus mesons.

Red quark

The decay of the red quark proceeds differently from that of the yellow and blue quarks in the simplest basic model we have constructed and where weak interactions proceed only through $SU(2) \times SU(2)$ interaction.

Since the model does not permit direct $X^0 - W_3^0$ mixing, the decay must proceed indirectly. There are two broad cases:

(1) $\frac{m_q}{m_G} > \frac{m_q}{m_G}$

The red quark mass exceeds the mass of the vector gluon. In this case, red quarks decay predominantly into neutrinos + gluons + mesons with lifetimes comparable to yellow and blue quark decays, e.g.

$$\begin{aligned}
 P_{\text{red}}^0 &\rightarrow G_\rho^- + \pi^+ + \nu_e, \quad \text{or } n_Y^0 + \gamma \quad (\text{if } n_Y^0 \text{ is lighter than } P_{\text{red}}^0) \\
 n_{\text{red}}^- &\rightarrow G_\rho^- + \nu_e, \quad G_\rho^- + \pi^+ + \pi^- + \nu_e
 \end{aligned}$$

(2) $\frac{m_q}{m_G} < \frac{m_q}{m_G}$

This is the more interesting case, in the sense that here charged red quarks may have long lives $\approx 10^{-8}$ secs. This is because n_R^- and λ_R^- can decay only by utilizing both $G^- \leftrightarrow W^-$ and $G^- \leftrightarrow X^-$ mixings; e.g.

$$\begin{aligned}
 n_R^- &\rightarrow e^- + \pi^0, \\
 \lambda_R^- &\rightarrow \mu^- + \eta.
 \end{aligned}$$

Also the purely leptonic decays are sizeable.

As remarked above, if the weak interaction gauge group is larger than $SU(2) \times SU(2)$ (for example $Sp(4) \times Sp(4)$), the distinction between yellow and blue vs. red quarks, so far as lifetime estimates are concerned, disappears, though the peculiar characteristic of only red quarks decaying into electrons or muons + mesons remains.

^{*)} If instead e^- is strange and ν_e charmed, the role of μ and e is reversed.

Proton lifetime

With all quarks decaying into leptons + mesons with lifetimes ranging between 10^{-8} - 10^{-12} secs., there is the question regarding the longevity of the proton. Is the proton sufficiently long-lived?

The proton's decay is a $\Delta B = 3$ transition, so that an effective (dimensionless) coupling parameter $\approx 10^{-9}$ for quark decays translates into a parameter $\approx 10^{-27}$ for proton decays. In spite of the smallness of this parameter, we find that the proton does live $\approx 10^{30}$ years, though the parameters of the model are stretched to their limit.

Empirically, the first estimate of a lower limit for the proton lifetime was made by Goldhaber, who estimating the amount of radioactivity released by proton decay from the human frame during a life span of three score years and ten - and from an estimate of deleterious effects of this radioactivity on the human frame - estimated that protons must live longer than 10^{16} years. Subsequent attempts at lifetime determination are listed in the following table.

<u>Experiment</u>	<u>lower limit to proton life</u>	<u>method</u>
Goldhaber	$> 1.4 \times 10^{18}$ years	Spontaneous fission of Th.232
Reines, Cowan and Goldhaber (1954)	$> 10^{22}$ years	Toulene detector 30 m below ground
Krupp and Reines (1964)	$> 10^{28}$ years	detector 585 m below ground
Gurr, Krupp and Reines (1967)	$> 8 \times 10^{29}$ years	detector 3200 m below ground
Reines and Crouch (1974)	$> 2 \times 10^{30}$ years	$p + \mu^+$ (5 events) re-analysis of 1967 experiment
Florini <u>et al.</u> (1974)	$> 10^{26}$ years	Mont Blanc tunnel experiments

It is worth remarking that from $\Delta F = 0$ and charge conservation, the proton positive muon (μ^+) transition can occur only if the minimum number of decay products is four or five:

$$P \rightarrow 3\nu + \pi^+ , \quad 4\nu + \mu^+ .$$

Thus the muon is likely to carry away only a small fraction of the proton's rest energy. This has important implications for the design of an experiment for detecting muons from proton decay - the muons are likely to be slow muons. In the design of the Gurr-Krupp-Reines experiment of 1967 (which gave a

signal of five muons possibly ascribable to protons decaying) the expectation was that the predominant decay mode of the proton may be

$$P \rightarrow \mu^+ + \gamma ,$$

so that muons would be fast. This particular decay mode with $|\Delta F| = 4$ is highly forbidden in our model.

VII. SLAC $e^+ + e^- \rightarrow \mu^+ + e^-$ EVENTS AS POSSIBLE DECAYS OF RED QUARKS AND ANTI-QUARKS

It is conceivable that red quark (pairs) have already been created at SLAC and the $\mu + e$ events are signals of their decays. Below we present a hypothetical scenario for this, which will hold provided the masses of particles concerned (gluons and quarks) satisfy the sequence $m(G) < m(q_{red}) < 2 \text{ GeV}$.

First, remark that if SPEAR does indeed see three-body leptonic decays of a parent (and anti-parent) produced in $e^+ + e^-$, this parent cannot be a quark - since purely leptonic decays of quarks, in our model, have too low an absolute probability. (The parent being detected cannot be a blue or yellow quark even if the decay is two-body, since blue and yellow quarks decay predominantly into neutrinos + mesons. Thus SPEAR may be producing blue and yellow quark pairs, but they are simply fuelling the energy crisis, insofar as their decays give rise to invisible neutrino energy.)

We suggest that the μe events are products of a double chain, where

$$e^+ + e^- \rightarrow q_{red}^- + q_{red}^+$$

with

$$q_{red}^- \rightarrow G^- + \nu \quad (\text{lifetime } 10^{-11} - 10^{-12} \text{ secs.})$$

followed by

$$G^- + e^- \rightarrow \bar{\nu}_e \quad \text{or} \quad \mu^- + \bar{\nu}_\mu \quad (\text{lifetime } \sim 10^{-14} \text{ secs.})$$

For this explanation to hold,

$$(1) \quad m(G) < m(q_{red}) \lesssim 2 \text{ GeV};$$

(2) As stated earlier, for such a low mass gluon G , the leptonic branching ratio $\approx 20-25\%$. For the production ratio (notwithstanding any colour suppression) for $e^+ + e^-$ producing $n_R^- \bar{p}_R^-$ and $\lambda_R^- \bar{\lambda}_R^-$, we estimate

$$R \geq \sum_{n_R^-, \lambda_R^-} (Q_{fla}^2)^2 \approx \frac{1}{9} + \frac{1}{9} = \frac{2}{9}$$

Thus the (μe) rate

$$\geq \frac{1}{2} \times \frac{2}{9} \times \left(\frac{1}{5} \text{ to } \frac{1}{4}\right) \times \rho$$

$$\approx 2\rho\%$$

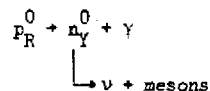
Here ρ is the unknown factor estimating quark-anti-quark recombination ratio (prior to real decays into gluons + neutrinos. With $\rho \approx \frac{1}{2}$ we obtain the sort of estimate SLAC make for μe rates.

If this indeed is the explanation of these events and SLAC is producing $q\bar{q}$ pairs, there are some peculiar characteristics which must be emphasised:

(1) Real $q\bar{q}$ pairs give final state hadrons displaying a jet structure. If partons are invisible quarks and must recombine to produce normal hadrons, it is difficult to understand the persistence of jet structure after the recombination process has taken place.

(2) As emphasised before, yellow and blue quarks decay into neutrinos - one more reason for the energy crisis.

(3) In addition to n_R^-, λ_R^- quark production, there is the probability (in fact, four times larger, since $R_{P_R^0, C_R^0} \geq (2/3)^2 = 4/9$) of neutral-pair (P_R^0, \bar{P}_R^0) and (C_R^0, \bar{C}_R^0) production in $e^+ + e^-$ events. These (red) quarks may decay with emission of monochromatic γ -rays.



if

$$m(n_Y^0) < m(P_R^0)$$

(alternatively, $P_R^0 \rightarrow G_p^- + \pi^+ + \nu_e$).

If $m(G) \neq m(q_{red}) \neq 2 \text{ GeV}$, the above explanation for (μe) events cannot hold. We must then ascribe SLAC events to three-body decays of heavy leptons, or (the less likely but not excluded) two-body decays of charmed or coloured mesons. Between heavy leptons and quarks there are the following crucial differences:

(1) Quarks mostly decay semileptonically, heavy leptons presumably mostly through purely leptonic modes.

(2) Production rate and scattering characteristics off matter for strongly interacting quarks are different than for heavy leptons.

(3) Neutral quarks carry the "hidden" flavour charge for asymptotic q^2 . Thus for

$$e^+ + e^- \rightarrow P_R^0 + \bar{P}_R^0$$

$$R \geq \left(\frac{2}{3}\right)^2 = \frac{4}{9}$$

Neutral heavy leptons, on the other hand, are unlikely to be produced copiously in $e^+ + e^-$ annihilation.

We turn finally to the question: can gluon mass be as light as 2 GeV or less? Pati, Sucher and Woo (unpublished) have estimated the branching ratios for a possible gluon of mass as low as 1.5 GeV produced in $e^+ + e^-$ annihilation in the Frascati region 1-2 GeV. They estimate

$G + e^+ + e^-$	1 keV
$+ \mu^+ + \mu^-$	1 keV
$\rightarrow \pi\pi\gamma, \eta'\gamma, 4\pi\gamma$	1 MeV
$+ 3\pi, 5\pi, \rho\pi \sim \frac{1}{10}$	$\sim 1 \text{ MeV}$
$+ 2\pi, 4\pi \sim \frac{1}{10}$	$\sim \frac{1}{10} \text{ MeV}$

and a photoproduction ratio

$$\gamma + N \rightarrow \frac{G + N}{\rho + N} + \frac{e^+ + e^- + N}{e^+ + e^- + N} \leq 10^{-3}$$

Apparently, at Frascati, a sweeping search for 1-2 MeV narrow resonances (1-2 MeV width) has not so far been conducted for the whole range of energies. I understand it is now in progress.

One final point; for a gluon as low in mass as 1 GeV, the effect on $(g-2)_\mu$ is estimated as $\approx \left(\frac{e^2}{4\pi^2}\right)^2 \frac{1}{12\pi^2} \left(\frac{m_\mu}{m_G}\right)^2 \approx 10^{-8}$

$$(m_G \sim 1 \text{ GeV}, \frac{r^2}{4\pi} \sim 5)$$

Since on present evidence $|\text{QED-experiment}| \leq 3 \times 10^{-8}$, one cannot exclude the existence of such particles from present $(g-2)_\mu$ measurements.

We have presented this scenario for SLAC μe events, assuming all masses involved are working in our favour, simply to emphasise that integer charge quarks - decaying semileptonically - are not excluded by any experiment yet performed. If gluon and quark masses exceed 2 GeV, SLAC is obviously not producing quarks in this experiment yet.

VIII. SUMMARY AND OUTLOOK

To summarize:

- (1) Integer-charge quarks decaying into leptons + mesons may exist. There is no quark dilemma for such unstable particles, which may already be produced in p-p collisions.
- (2) Lepto-production sum rules do not favour fractional charge-quark models over integer-charge quarks. In lepto-production colour is not overbright, but should be seen through gluons. There is no suppression of colour in N-N experiments.
- (3) Integer-charge yellow and blue quarks predominantly decay into neutrinos + mesons with lifetimes $\approx 10^{-11} - 10^{-12}$ secs. and are perhaps uninteresting. Red quarks may be more interesting in the following sense: if vector gluons with masses lower than red quarks exist, and if $m(q_{\text{red}}) < 2 \text{ GeV}$, the production and decays of red quark-anti-quark pairs may provide a possible explanation of SLAC (μe) events. If such (low mass) gluons (lighter than quarks) do not exist, red quarks may have long lives $\sim 10^{-8}$ secs.

These predictions are based on the basic model suggested in 1973. This model assumes that (1) there are no heavy quarks or heavy leptons, (2) electrons and muons carry the same colour ($L_{\text{lepton}} = L_e + L_\mu$), (3) the weak interactions are $SU_L(2) \times SU_R(2)$ and not more complex (e.g. $Sp_L(4) \times Sp_R(4)$), (4) the predictions may depend also on the structure of the Higgs-Kibble particles. The heavy leptons - if found - can without difficulty be accommodated into the model as one further basic fermionic multiplet. However, the details of predictions regarding quark decays will alter to the extent that

red quarks will in all cases become as short-lived as yellow and blue quarks. At the present time the only experiment which appears to call for the existence of heavy leptons is the SLAC μe experiment (and none which calls for heavy quarks). If SLAC events find an explanation in terms of red quark-anti-quark decays as discussed in the previous section, there would be no need to introduce any heavy particles and one may get by with the rather elegant basic model.

Undoubtedly the Gell-Mann-Zweig quark concept (as one more stage in the architecture of matter) was the most important concept invented in recent times.

If quarks do exist as physical particles, does this mean that we must expect, at the next energy range, the existence of PREQUARKS (PREONS) and then perhaps the pre-pre-quarks and so on? Does the chain end somewhere, as it appears to do for leptons (with neutrinos and electrons)?

My feeling is that questions like this are not well posed in terms of "elementary" constituents of matter or "elementary" fields - such questions are better posed in terms of "elementary charges". Our basic concern can be: how many elementary charges are there? Is there an end to the succession $SU(2)$, $SU(3)$, $SU(4)$ - or even, are we looking at these charges in the right way? I do not think, to this issue, the precise complexion of elementary entities, appearing as physical particles, has much direct relevance, though some choices may be more distinguished than others. (This much one may concede to the bootstrap philosophy of the last decade.) But having said that, and being guided by the observations (1) that "elementary leptons" - well described by local elementary fields - do appear to exist, and (2) that there should be no absolute distinction between leptons and hadrons as representations of the charge algebra, I tend to believe that the hadronic chain ends in the same manner as the leptonic, i.e. with some sort of visible *) quarks or PREONS.

There appear to be at present two or three different ways of understanding the nature of charge.

*) The convinced confiner can turn the argument the other way round and posit that perhaps there exist pre-leptons which are on par with quarks and also confined. This is a logical possibility. On the basic level, our criticism is directed to the theories which postulate two distinct ends of the chain - one for hadrons and quite a different one for leptons. On the ^{practical level,} main thrust of this note is that - with the case we have made out for integer-charge visible quarks - it is experiment alone that is the final arbiter of what stage in the architecture of matter we have reached at present energies.

(A) The humble suggestion - which one must not lose sight of - exemplified by the hydrogen atom's $O(4)$ which seeks the origin of conserved quantities in the dynamical accidents of particular Lagrangians, when solutions with special boundary conditions are sought. The present preoccupation with the so-called topological quantum numbers is a part of the same mode of thinking. From this point of view, there may be no finality to the symmetry group chain; possibly the higher we go in the scale of energies, the more quantum numbers we may discover. This is in accord with the ideas of Wheeler on the topological nature of electric charge. ¹

(B) The Einstein path. Einstein found a deeper significance for gravitational charge in terms of space-time concepts. Einstein himself unfortunately never stressed charge; his preoccupation was always with the gravitational field and, in later life, with the electromagnetic field. Klein-Kaluza tried to extend Einstein's ideas, concentrating more on the charge concept. They postulated a fifth dimension - something very small $\approx 10^{-33}$ cms, so that we cannot directly apprehend it - to understand electric charge. In the spirit of Klein-Kaluza, the dual modelists (Schwarz, Cremmer, Smerck, etc.) suggest taking their $(4+6)$ dimensions seriously; proposing for example that the extra $O(6)$ they need for consistency of dual models is isomorphic to $SU(4)$. Freund ⁷ on the other hand, has suggested that there are extra dimensions but they are "fermionic", in the manner of the dimensions introduced into Wess-Zumino's supersymmetry by Strathdee and myself. The advantage of having extra dimensions as fermionic degrees of freedom lies in that the observability problems are less severe (or non-existent) for these. Nath and Arnowitt ⁷ have claimed that internal symmetry groups ($U(1)$ or $U(2)$ or $U(3)$ etc.) carried by these fermionic dimensions are uniquely determined once we specify the analogue of Minkowskian boundary conditions in the fermionic superspaces under discussion.

(C) Instead of introducing extra dimensions, one may rely on extended number-algebras to specify nature's preference for some symmetry group over others. Deepest work in this direction has come from Gürsey ⁸ who has shown that if octonian algebra is assumed to be the hallmark of particle physics, then exceptional Lie groups G_2, E_6, E_7, E_8 would play a decisive role. As emphasised by Gell-Mann, the important remark is these groups all contain $SU(3)$ or $SU(3) \times SU(3)$ or $SU(6)$ as subgroups, so that somehow $SU(3)$ - but not $SU(4)$ - structures acquire a deep and basic significance.

Perhaps none of these remarks is deep enough yet. But it is through the appreciation that the charge concept is what underlies particle physics, that our generation, in its humble way, is beginning where Einstein left off.

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