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QUARK-LEPTON UNIFICATION AND PROTON DECAY *

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ABSTRACT

Complexions for proton decay arising within a maximal symmetry for quark-lepton unification, which leads to spontaneous rather than intrinsic violations of B, L and F are considered. Four major modes satisfying $\Delta B = -1$ and $\Delta F = 0, -2, -4$ and -6 are noted. It is stressed that some of these modes can coexist in accord with allowed solutions for renormalization group equations for coupling constants for a class of unifying symmetries. None of these remarks is dependent on the nature of quark charges. It is noted that if quarks and leptons are made of constituent preons, the preon binding is likely to be magnetic.

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I. INTRODUCTION

The hypothesis of grand unification [1-3] serving to unify all basic particles - quarks and leptons - and their forces - weak, electromagnetic as well as strong - stands at present primarily on its aesthetic merits. It gives the flavour of synthesis in that it provides a rationale for the existence of quarks and leptons by assigning the two sets of particles to one multiplet of a gauge symmetry G. It derives their forces through one principle-gauge unification.

With quarks and leptons in one multiplet of a local spontaneously broken gauge symmetry G, baryon and lepton number conservation cannot be absolute. This line of reasoning had led us to suggest in 1973 that the lightest baryon - the proton - must ultimately decay into leptons [2]. Theoretical considerations suggest a lifetime for the proton in the range of 10^{28} to 10^{33} years [2-5]. Its decay modes and corresponding branching ratios depend in general upon the details of the structure of the symmetry group and its breaking pattern. What is worth noticing at this junction is that studies of (i) proton decay modes, (ii) $n-\bar{n}$ oscillation [6], (iii) neutrinoless double β-decay and (iv) the weak angle [7] $\sin^2\theta_W$ are perhaps the only effective tools we would have for sometime to probe into the underlying design of grand unification.

Experiments [8] are now underway to test proton stability to an accuracy one thousand times higher than before . In view of this, we shall concentrate primarily on the question of expected proton decay modes within the general hypothesis of quark-lepton unification and on the question of intermediate mass scales filling the grand plateau between 10^2 and 10^{15} GeV, which influence proton decay. At the end we shall indicate some new features, which may arise if quarks and leptons are viewed - perhaps more legitimately - as composites of more elementary objects - the "preons".

Much of what we say arises in the context of maximal quark-lepton unifying symmetries of the type proposed earlier [9]. we specify such symmetries in detail later. One characteristic feature worth noticing from the beginning is that within such symmetries a linear combination of baryon and lepton numbers as well as fermion number F are locally gauged and are therefore conserved in the gauge Lagrangian. They are violated spontaneously and unavoidably as the associated gauge particles acquire masses. The purpose of the talk would be many-fold:

1) First to restress in the light of recent developments that within maximal symmetry framework the proton may in general decay via four major modes F1), which are characterized by a change in baryon number by -1 and that in fermion number (defined below) by 0, -2, -4 and -6 units F2)

$$\left.\begin{array}{l} p \to 3\nu + \pi^+ \\ p \to 2\nu + e^- + \pi^+\pi^+ \text{ etc} \end{array}\right\} \left.\begin{array}{l} \Delta F = 0 \\ \Delta B_q = -3,\ \Delta L = +3 \end{array}\right\} \Delta(B-L) = -4 \tag{1}$$

$$\left.\begin{array}{l} p \to e^-\pi^+\pi^+,\ \nu\pi^+,\ e^-K^+\pi^+ \\ p \to e^+\nu_1\nu_2, e^+e^-e^-\pi^+\pi^- \text{ etc} \end{array}\right\} \left.\begin{array}{l} \Delta F = -2 \\ \Delta B_q = -3,\ \Delta L = +1 \end{array}\right\} \Delta(B-L) = -2 \tag{2}$$

$$\left.\begin{array}{l} p \to e^+\pi^0,\ \bar{\nu}_e\pi^+,\ \mu^+K^0 \\ p \to \mu^+\pi^0,\ \bar{\nu}_\mu\pi^+,\ e^+e^+e^- \text{ etc} \end{array}\right\} \left.\begin{array}{l} \Delta F = -4 \\ \Delta B_q = -3,\ \Delta L = -1 \end{array}\right\} \Delta(B-L) = 0 \tag{3}$$

$$p \to 3\bar{\nu} + \pi^+,\ e^+\bar{\nu}_1\bar{\nu}_2, e^+e^+\bar{\nu}\pi^- \text{ etc}\Big\} \left.\begin{array}{l} \Delta F = -6 \\ \Delta B_q = -3,\ \Delta L = -3 \end{array}\right\} \Delta(B-L) = +2 \tag{4}$$

(Here B_q denotes quark number which is +1 for all quarks, -1 for antiquarks and 0 for leptons. The familiar baryon number F3) B, which is +1 for the proton, is one third of quark number ($B \equiv B_q/3$). L denotes lepton number which is +1 for $(\nu_e, e^-, \mu^-, \nu_\mu, \ldots)_{L,R}$, -1 for their antiparticles and 0 for quarks. Fermion number F

F1) That the proton may decay via all these four modes (ΔF = 0, -2, -4 and -6) was to our knowledge first observed in Ref.9. The modes ΔF = 0 and -4 occur within specific models of Refs.2 and 3, respectively, while the questioning of baryon number conservation (Ref.2) is based on more general considerations and is tied simply to the idea of quark-lepton gauge unification, together with spontaneous symmetry breaking.

F2) We are not listing decay modes satisfying ΔB = -1 and ΔF = +2, 4 etc. corresponding to $p \to$ (5 or 7 leptons) + π's. These appear to be suppressed compared to those listed.

F3) The reader may note that in our previous papers we had by convention chosen to call quark number B_q as baryon number B. Therefore the 15th generator of $SU(4)_{col}$ (Ref.2) which was written as (B-3L) stood for (B_q - 3L). With the more conventional definition of baryon number, as adopted in the present note, B_q - 3L is just 3(B-L).

is the sum of B_q and L: $F \equiv B_q + L$. Since for proton decay, quark number must change by a fixed amount $\Delta B_q = -3$, there is a one-one relationship between change of fermion number F and that of any other linear combination of B_q and L for example of $[(B_q/3) - L] = B - L$ for the proton decay modes as exhibited in (1)-(4).

2) Our main emphasis here is that these four alternative decay modes can in general coexist.

We wish:

3) To stress that observation of any three of the decay modes satisfying ΔF = 0, -2 and -6 would unquestionably signal the existence of one or several intermediate mass scales filling the plateau between 10^2 and 10^{15} GeV. [Existence of such intermediate mass scales is a feature which naturally rhymes with (a) maximal symmetries and the consequent spontaneous rather than intrinsic nature of B, L, F violations and (b) partial quark-lepton unification at moderate energies $10^4 - 10^6$ GeV.] [2,10]

4) To point out that the complexions of proton-decay selection rules alter if one introduces intrinsic left-right symmetry in the basic Lagrangian thereby permitting the existence F4) of ν_R's parallel to ν_L's and

5) To stress that none of the remarks (1)-(4) is tied to the nature of quark charges. These remarks hold for integer as well as fractional quark charges. [In the later case (fractional charges), SU(3) colour symmetry is exact.]

To motivate these remarks let us first specify what we mean by "maximal" symmetry. Maximal symmetry [9] corresponds to gauging all fermionic degrees of freedom with fermions consisting of quarks and leptons. Thus with n two component left-handed fermions F_L plus n two component right-handed fermions F_R, the symmetry G is $SU(n)_L \times SU(n)_R$. One may extend the symmetry G by putting fermions F_L and antifermions F_L^c (as a substitute for F_R) in the same multiplet. In this case the symmetry G is SU(2n), which is truly the maximal symmetry of 2n two component fermions. As an example, for a single family of two flavours and four colours including leptonic colour, n = 8 and thus G = SU(16). One word of qualification: Such symmetries generate triangle anomalies, which are avoided however by postulating that there exist a conjugate mirror set of fermions $F^m_{L,R}$ supplementing the basic fermions $F_{L,R}$ with the helicity flip coupling represented by the discrete symmetry

F4) Note that in this case one must assume that ν_R and ν_L combine to form a light 4 component Dirac particle and that $m_{W_R} \gg m_{W_L}$. (To conform with astrophysical limit one may need $m_{W_R} \gtrsim 50\ m_{W_L}$, see G. Steigman, Erice Workshop Proceedings, March 1980.) The alternative of ν_R acquiring a heavy Majorana mass is of course permissible; but such heavy ν_R will not be a decay product in proton decay.

$(F_{L,R} \longleftrightarrow F^m_{R,L})$. Thus by "maximal" symmetries we shall mean symmetries which are maximal upto the discrete mirror symmetry.

Though old, it is now useful to recall the argument leading to violations of B, L and F. If all quark-lepton degrees of freedom are gauged locally as in a maximal symmetry G specified above,[F5)] then fermion number $F \equiv B_q + L = 3B + L$ as well as an independent linear combination of baryon and lepton numbers $(B + xL)$ are among the generators of the local symmetry G. Now if all gauge particles[F6)] with the exception of the photon and (for the case of fractionally charged quarks) the octet of gluons, acquire masses spontaneously, then both fermion numbers F and $(B + xL)$ must be violated spontaneously, as the associated gauge particles acquire their masses. The important remark here is that even though B, L and F are conserved in the basic Lagrangian, they are inevitably and <u>unavoidably</u> violated spontaneously[F7)].

Instead of the maximal symmetry G, one may of course choose to gauge a <u>subgroup</u> $\mathcal{G} \subset G$. But as long as the subgroup $\mathcal{G}$ assigns quarks and leptons into one irreducible multiplet, there are only two alternatives open. Either the subgroup $\mathcal{G}$ still possesses an effective fermion number F and/or $(B + xL)$ among its generators[F8)]. In this case these must be violated <u>spontaneously</u>

F5) For the case of the lepton number being the 4th colour (Ref.2) this generator is $\propto B_q - 3L = 3(B-L)$.

F6) From the limits on Eötvos type experiments, one knows that no massless gauge particle couples to B, L or F leading to an effective four fermion coupling $\gtrsim G_{Newton} \times 10^{-8}$.

F7) Truly the argument above demands violations of linear combinations $F = (3B + L)$ and $(B + xL)$, i.e. at least B or L must be violated. Several authors have remarked that it is possible to introduce global quantum numbers within the quark-lepton unification hypothesis, which would preserve proton stability (see Ref.11). But all simple models end up with an unstable proton (Refs.1-3).

F8) For example $[SU(4)]^4$ and $[SU(6)]^4$ contain (B-L) as a local symmetry, but not F (though F is a global symmetry in the basic Lagrangian of these models). SU(16) operating on 16 folds of e, μ and τ family fermions (see Table I) is a subgroup of $[SU(16)]^3$ and SU(48). It contains B-L and F with $B = B_e + B_\mu + B_\tau$ and likewise for L and F.

for reasons stated above. Or the gauging of subgroup $\mathcal{G}$ leads to a "squeezing" of gauges of the maximal symmetry G such that one and the same gauge particle couples for example to the diquark $(\bar{q}^c q)$ as well as to the quark-lepton $(\bar{q}\ell^c)$ currents.[F9)] In this case, baryon, lepton and fermion numbers are violated <u>explicitly</u> through the gauge interaction itself. One way or another, some linear combinations of B and L must be violated; the basic reason in either case being the same - i.e. the appearance of quarks and leptons in the <u>same</u> symmetry multiplet.

Spontaneous and explicit violations of B, L and F can in general lead to similar predictions for proton decay. But the two cases would differ characteristically from each other at superhigh temperatures, where explicit violations would acquire their maximal gauge strength with the superheavy gauge masses going to zero, while spontaneous violations would in fact vanish.

II. MODELS OF GRAND UNIFICATION

It is useful to see the interrelationships between different types of unification models. The simplest realization of the idea of quark-lepton unification is provided by the hypothesis that "<u>lepton number is the fourth colour</u>.[2] For a single family of (u,d) flavours, the corresponding multiplet is

$$(F_e)_{L,R} = \begin{bmatrix} u_r & u_y & u_b & u_\ell = \nu_e \\ d_r & d_y & d_b & d_\ell = e^- \end{bmatrix}_{L,R} \qquad (5)$$

with r, y, b and ℓ denoting red, yellow, blue and lilac colours, respectively. The corresponding local symmetry is

$$\mathcal{G} = SU(2)_L \times SU(2)_R \times SU(4)'_{L+R} , \qquad (6)$$

where $SU(2)_{L,R}$ operates on the flavour indices $(u,d)_{L,R}$ and $SU(4)'_{L+R}$ operates on the four colour indices (r,y,b,ℓ). It is the SU(4) colour symmetry which intimately links quarks and leptons. The symmetry $\mathcal{G}$ has three features: i) First it is one of the simplest subunification models containing the low energy symmetry $SU(2)_L \times U(1) \times SU(3)'_{L+R}$ on the one hand and realizing quark-lepton

F9) Examples of this type are SU(5) (Ref.3) and SO(10) (Ref.12). SU(5) does not contain B-L or F as local symmetries. SO(10) contains (B-L) but not F. Both SU(5) and SO(10) violate B, L and F explicitly in the basic gauge Lagrangian.

unification on the other. It gauges through the SU(4) colour symmetry (linking quarks and leptons) the combination $(B_q - 3L) = 3(B-L)$ as a local symmetry. ii) Second, it is non-abelian and thus provides a simple raison for the quantization of charges. iii) Its gauge structure is left-right symmetric [14]. (Indeed the idea of lepton number as the fourth colour requires that neutrinos must be introduced with left and right helicities [F11] and thereby the basic matter multiplet must be left-right symmetric given that quarks enter into the basic Lagrangian with both helicities.)

The symmetry $\mathcal{G}$, because of its simplicity, might be the right stepping stone towards grand unification. It should of course be viewed as a subunification symmetry as it contains at least two gauge coupling constants - one [14] for $SU(2)_{L,R}$ and the other for $SU(4)'_{L+R}$. In other words, it should be regarded as part of a bigger unifying symmetry G possessing a single gauge coupling constant. There are a number of candidates for G, which do contain the sub-unification symmetry $\mathcal{G}$. Table I provides a list of some of these symmetries.

Table I †

$SU(2)_L \times SU(2)_R \times SU(4)'_{L+R} \rightarrow$

(1) $[SU(4)]^4 \cdots\rightarrow (4 \text{ flavours} \times 4 \text{ colours})_{e,\mu} + (4 \text{ flavours} \times 4 \text{ colours})_{\tau,\tau'}$ (Ref.2)

(2) $[SU(6)]^4 \cdots\rightarrow (6 \text{ flavours} \times 6 \text{ colours})$ (Ref.15)

- -

(3) Maximal symmetry for a family

$SU(16) \cdots\rightarrow \underset{\sim}{16}_e + \underset{\sim}{16}_\mu + \underset{\sim}{16}_\tau$

$16_e = [u, \nu_e \,\vdots\, d, e^- | d^c, e^c \,\vdots\, u^c, \nu^c]_L$ (Refs.9,16)

- -

(4) $SO(10) \overset{F12)}{\cdots\rightarrow} \underset{\sim}{16}_e + \underset{\sim}{16}_\mu + \underset{\sim}{16}_\tau$ (Ref.12)

(5) $E_6 \cdots\rightarrow \underset{\sim}{27}_e + \underset{\sim}{27}_\mu + \underset{\sim}{27}_\tau$ (Ref.17)

† The symmetries $[SU(n)]^4$ and SU(16) require the presence of mirror fermions for cancellation of anomalies (see discussion in Sec.I).

F11) With ν_R being distinct from $\bar{\nu}_R$.

F12) SO(10) is the simplest extension of $SU_L(2) \times SU_R(2) \times SU_{L+R}(4)'$ because the latter is isomorphic with $SO(4) \times SO(6)$.

All the unifying symmetries listed in Table I are left-right symmetric. By contrast one may consider the left-right asymmetric model [3] SU(5), which is the smallest grand unifying symmetry of all with the multiplet structure

$$(\bar{5} + 10)_e + (\bar{5} + 10)_\mu + (\bar{5} + 10)_\tau$$

in which the right-handed neutrinos $(\nu_{e,\mu,\tau})_R$ are missing. Note that in contrast to the models listed in Table I the multiplet structure for SU(5) is reducible; $(\bar{5} + 10)$ within one family.

Even if Nature is intrinsically left-right asymmetric, from the point of view of maximal gauging, the underlying family symmetry would be SU(15), for which the $(\bar{5} + 10)$ form a single 15-fold. It is worth remarking that SU(15), SO(10) and SU(5) may all be viewed as subgroups of SU(16). The symmetry SU(16) gauges both fermion number F as well as B-L as local symmetries and thereby conserves both in the gauge Lagrangian before their spontaneous violation. SO(10), however, gauges B-L (since it contains $SU(2)_L \times SU(2)_R \times SU(4)'_{L+R} \approx SO(4) \times SO(6)$) but not the fermion number F. In fact F is violated so far as the SO(10) gauge Lagrangian is concerned due to squeezing of SU(16) gauges in the sense mentioned earlier. By contrast SU(5) gauges ~~neither~~ F nor B-L as local symmetries. For SU(5) like SO(10), F is explicitly violated in the gauge Lagrangian. Depending upon the choice of the Higgs structure and the fermion-Higgs Yukawa interactions, B-L may or may not be a good global quantum number for SU(5). (For example, the simplest SU(5) model with a $\underset{\sim}{24}$ and $\underset{\sim}{5}$ of Higgs conserves (B-L); but this is not a general property of SU(5).)

In general, since $SU(16) \supset SO(10)$ and SU(5), it may descend spontaneously to $SU(2) \times U(1) \times SU(3)$ via SO(10) or SU(5) as intermediate steps. Alternatively, it may descend via $SU(8)_A \times SU(8)_B \times U(1)_F$, where $U(1)_F$ gauges fermion number and $SU(8)_A$ and $SU(8)_B$ operate on the octets of F_L and F_L^C of a given family. By introducing Higgs corresponding to both types of descent, one may descend directly to $SU_C(2) \times SU_R(2) \times SU(4)$ or even to $SU_L(2) \times SU_R(2) \times SU_{L+R}(3) \times U(1)$. Low energy phenomena including complexions for proton decay would depend upon which of these alternative routes is chosen. Some of these possibilities are exhibited in Fig.1.

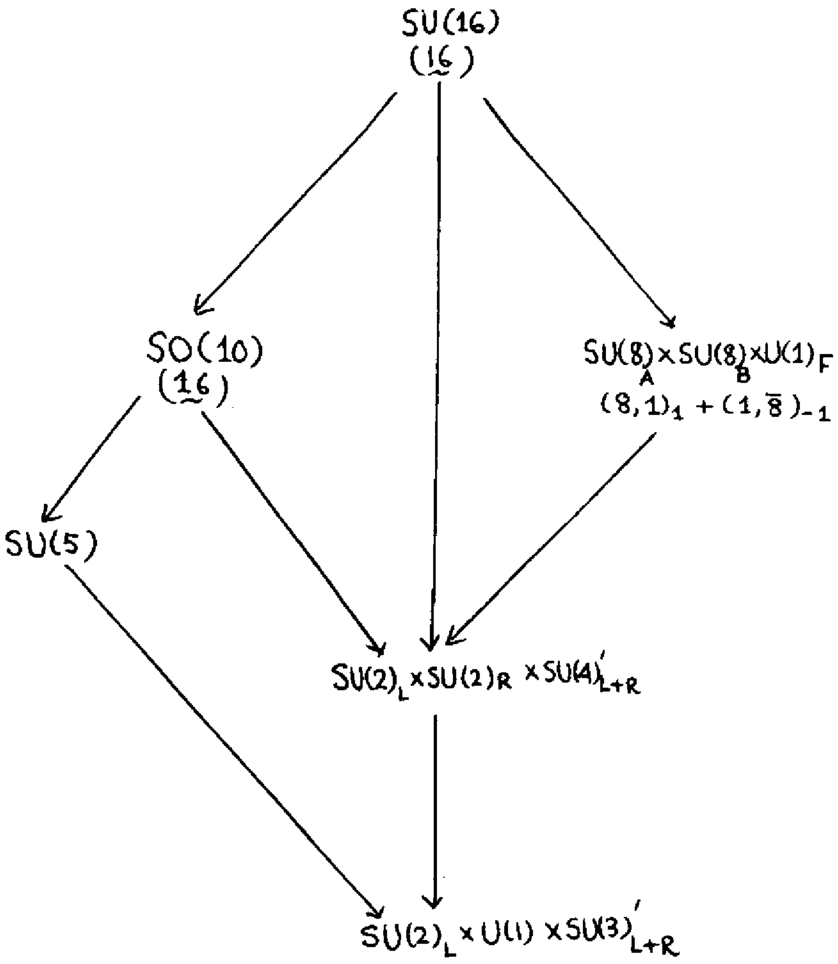


Fig.1: Some alternative routes for spontaneous descent of SU(16). to low energy symmetry. The subscripts ±1 for (8,1) and (1,$\bar{8}$) denote the respective fermion numbers.

Maximal symmetry and spontaneous violations of B, L and F

A maximal symmetry SU(2n), which puts n left-handed quarks and leptons as well as their charge conjugate fields within the same multiplet $F = [q, \ell | q^c, \ell^c]_L$ generates the sets of gauge fields shown in Fig.2.

We note that within maximal gauging each of the gauge particles of the Lagrangian before spontaneous breaking carries definite baryon, lepton and fermion numbers and thus these quantum numbers are conserved. The violations of these quantum numbers arise however as the gauge particles (barring the photon and the octet of gluons for the fractional charge quark case) acquire masses through spontaneous breakdown of the local symmetry G. The violations come about in two distinct ways.

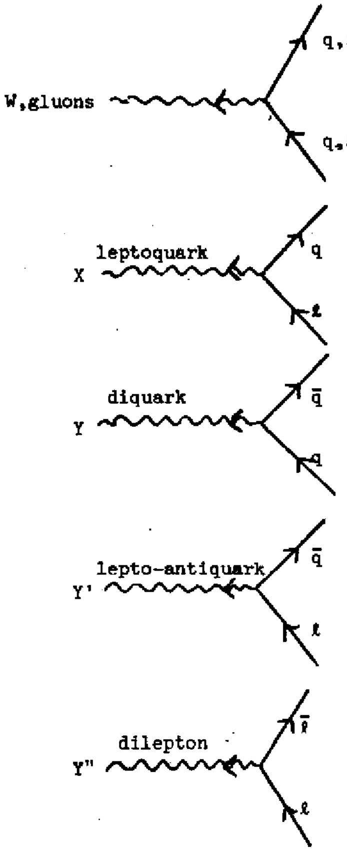
(a) Gauge mixing: Spontaneous symmetry breaking induces mixings[9] of gauge particles carrying different sets of values of B, L and F and this leads to violations of these quantum numbers. In particular, the $\Delta(B-L) = 0$, $\Delta F = -4$ and $\Delta(B+L) = 0$, $\Delta F = -2$ proton decays arise through the gauge mixings noted below:

Mixing	Symmetry violation	Decay mode
$Y \longleftrightarrow \bar{Y}'$	$\Delta B_q = -3$, $\Delta L = -1$, $\Delta F = -4$	$p \to \bar{\ell}$ + mesons
$Y \longleftrightarrow \bar{X}$	$\Delta B_q = -3$, $\Delta L = +1$, $\Delta F = -2$	$p \to \ell$+ mesons .

These two kinds of spontaneously induced mixings are exhibited in Figs.3a and 3b, respectively. For SU(16) the $Y \longleftrightarrow \bar{Y}'$ mixing leads to $\Delta F = -4$ decays. Such mixings can be induced for example by Higgs of the type[F13] $\Omega^{\{CD\}}_{\{AB\}}$, where A, B, C, D range over 1-16. These violate B, L, F but respect (B-L). If in addition we also introduce Higgs of the adjoint (255) type ξ^B_A, SU(16) breaks down to $SU_L(8) \times SU_R(8) \times U_F(1)$. The descent to $SU_L(2) \times SU_R(2) \times SU(4)$, through both these types of Higgs and the fact that X-gauge bosons belong to SU(4) must ensure that $m_X^2 \lesssim \Delta^2_{YY'} \lesssim m_Y^2, m_{Y'}^2$ where $\Delta_{YY'}$ is the mixing parameter in the Y-$\bar{Y}'$ mass matrix.

F13) The detailed patterns of symmetry breaking as correlated with the helicities of particles involved in the decay will be presented in a paper with J. Strathdee.

Gauge particle-qeuntum numbers



F = 0, B_q = L = 0

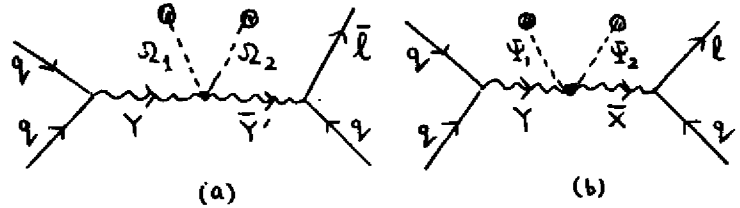
F = 0, B_q = - L = -1

F = 2, B_q = 2, L = 0

F = +2, B_q = L = +1

F = 2, B_q = 0, L = +2

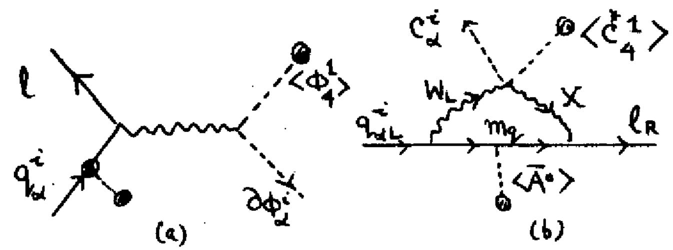
Fig.2: Gauge particles within a maximal symmetry. Here B_q, L and $F \equiv B_q + L$ denote quark, lepton and fermion numbers, respectively, as defined in Sec.I.



(ΔF = -4) p → $\bar{\ell}$ + mesons

(ΔF = -2) p → ℓ + mesons

Figs. 3a,b: Spontaneous violations of B,L and F in a maximal symmetry leading to gauge mixings. These induce, for example, $\Delta F = -4$ and -2 proton decays. $\Omega_{1,2}$ and $\Psi_{1,2}$ are Higgs fields (see text).



Figs. 4a,b: Spontaneous violations of B,L (and in general F) leading to effective Yukawa transitions: $q^i_\alpha \to \ell + \phi^i_\alpha$. These transitions in third order induce $\Delta F = 0$ proton decays: p → 3ℓ + mesons (and analogously $\Delta F = -6$ decays: p → 3$\bar{\ell}$ + mesons). See text.

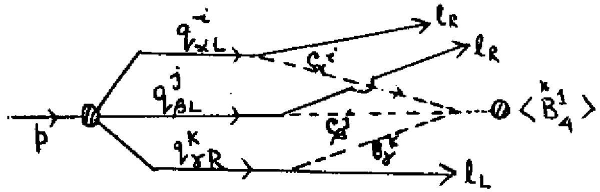


Fig.5: $\Delta F = 0$ proton decays through spontaneous violations of B and L. These utilize the effective Yukawa transitions of Fig.4 thrice. Note that the mechanism of Figs. 3, 4 and 5 apply to integer as well as fractionally charged quarks.

The amplitude for $\Delta F = -4$ transition (generated via Fig.3a) is:

$$A(3q \to \bar{\ell})_{\Delta F=-3} \approx (g^2 \Delta^2_{YY'})/m_Y^2 m_{Y'}^2 \quad .$$

This is bounded below by $g^2 m_X^2/m_Y^4$ and above by g^2/m_Y^2. The lower and upper bounds correspond to the minimal and maximal values of $\Delta^2_{YY'}$ mentioned above.(Note that the maximal value $\Delta^2_{YY'} = m_Y^2 - m_{Y'}^2$, is the case for example for SO(10) which contains $Y_s = (Y + \bar{Y}')/\sqrt{2}$ type gauge particles only.) This is recoverable from SU(16) when $(Y - \bar{Y}')/\sqrt{2}$ gauge mesons are of infinite mass.

The $Y \to \bar{X}$ mixing leads to $\Delta F = -2$ transitions (Fig.3b). This could arise for example from VEV's of a Higgs of the type $\Psi^{[CD]}_{[AB]}$. Writing $\langle\Psi\rangle$ as $\langle\Psi_1\rangle + \langle\Psi_2\rangle$ where $\langle\Psi_2\rangle$ conserves $SU_L(2) \times SU_R(2) \times SU(4)$ and $\langle\Psi_1\rangle$ violates $SU_L(2)$ as well as $SU_R(2)$ (with the corresponding components transforming as $I_L = \frac{1}{2}$ and $I_R = \frac{3}{2}$), it follows that $\langle\Psi_1\rangle \lesssim m_{W_L}/g$, while $\langle\Psi_2\rangle$ may be as large as [F14] m_X/g. Thus

$$A(3q \to \ell)_{\Delta F=-2} \approx g^2 \Delta_{XY}/m_X^2 m_Y^2 \lesssim g^2 \frac{m_{W_L} m_X}{m_X^2 m_Y^2} \left(\text{or } g^2 \frac{m^2_{W_L}}{m_X^2 m_Y^2}\right) .$$

It is worth noting from the above that if $\Delta^2_{YY'}$ has its maximal value $\sim m_Y^2$, then $\Delta F = -4$ amplitude would always dominate over $\Delta F = -2$ amplitude by a factor $\gtrsim (m_X/m_{W_L}) >> 1$. The two amplitudes would be comparable however if $\Delta^2_{YY'}$ is much smaller than m_Y^2 (see next section).

F14) We face here, as elsewhere, the problem of gauge hierarchies; i.e. the question, are all VEV's of Higgs fields always of the same order of magnitude? If this is the case $\langle\Psi_2\rangle$ is also of order (m_{W_L}/g).

(b) The violations of B,L and F may also arise through spontaneously induced three point Yukawa transitions of the type $q \to \ell + \phi$ (see Figs.4a and 4b)

$$q^i_{\alpha L} \to \nu_R + C^i_\alpha + \langle \overset{*}{C}{}^1_4 \rangle + \langle \bar{A}^o \rangle$$

$$q^i_{\alpha R} \to \nu_L + B^i_\alpha + \langle \overset{*}{B}{}^1_4 \rangle + \langle A^o \rangle$$

$$d_{\alpha L} \to e^-_R + C^1_\alpha + \langle \overset{*}{C}{}^1_4 \rangle + \langle A^o \rangle$$

$$d_{\alpha R} \to e^-_L + B^1_\alpha + \langle \overset{*}{B}{}^1_4 \rangle + \langle \bar{A}^o \rangle \quad . \qquad (7)$$

Here i and α denote flavour and SU(3) colour indices, respectively. The fields A, B and C which are identical to those introduced in Ref.2, transform as $(2,2,1)$ $(1,2,\bar{4})$ and $(2,1,\bar{4})$ respectively under $SU(2)_L \times SU(2)_R \times SU(4)_{L+R}$. Under SU(16), A belongs to a $[16 \times 16]_{symmetric}$ representation, while C and $B^\dagger$ together make a 16 fold. The fields C^1_4 and $\overset{*}{B}{}^1_4$ have the same quantum numbers within a 16 fold as ν_{eL} and ν^c_{eL} respectively, while A^o possesses $I_{3L} = -I_{3R} = -1/2$. The VEV $\langle \overset{*}{C}{}^1_4 \rangle$ and $\langle A^o \rangle$ are of order (m_{W_L}/g), while $\langle \overset{*}{B}{}^1_4 \rangle$ must be of order (m_{W_R}/g) or (m_X/g), whichever is lower. The effective Yukawa transitions (7), used thrice, induce $\Delta F = 0$ proton decays (see Fig.5) of the type [18]

$$p \to \nu_L \, \nu_R \, \ell_{L,R} + \pi\text{'s} \quad , \qquad (8)$$

where $\ell_{L,R}$ denotes either the charged or the neutral lepton. These transitions are made possible through quartic scalar interactions which permit for example $(C^1_1 + C^2_2 + B^2_3)$ to make a transition into B^{*1}_4 and thereby disappear into vacuum through $\langle B^{*}_{14} \rangle \neq 0$ (see discussion later). Fermi statistics together with the colour singlet nature of the proton inhibits both neutrinos in the final state from having the same helicity [18] (see (8)).

An analogous mechanism induces the Yukawa transitions $q^1_\alpha \to \bar{\ell} + \chi^1_\alpha$ which in third order induce proton decays satisfying $\Delta F = -6$

$$p \to 3q = (3\bar{\ell} + \pi\text{'s}) + 3\chi \to (3\bar{\ell} + \pi\text{'s}) + \langle \chi^{*1}_4 \rangle . \qquad (9)$$

In accord with the observation in Ref.9, the above mechanisms show that all four modes for proton decay satisfying $\Delta F = 0, -2, -4$ and -6 can arise within a maximal symmetry G. Their relative rates would depend upon the associated gauge masses and the mixing parameters, which in turn depend upon the parent symmetry G as well as upon its breaking pattern.

Two common features of these mechanisms are worth noting:

i) They utilize only spontaneous rather than ~~explicit~~ violations of B, L and F. None of these would be operative if the vacuum expectation values of all the relevant Higgs fields were set to zero.

ii) None of these mechanisms is tied to the nature of quark charges. They hold for quark charges being either integral or fractional with SU(3) colour local symmetry either being broken spontaneously and softly or remaining exact.

[We would like to make a small digression here. Our suggestion of quark-lepton unification of 1972 has been misunderstood in this regard - as though it is tied to integer charges for quarks. A bit of history is perhaps relevant. During the years 1972-74 almost everyone accepted fractional charges and absolute confinement. Our contention, however, was that both possibilities - fractional as well as integral charges for quarks - arise within the same unification hypothesis. For example, the hypothesis "lepton number is the fourth colour" permits both charge patterns depending only upon the nature of spontaneous symmetry breaking.[2] Since it was a logical possibility, we built the theory of integer charges for quarks and possible "quark liberation" so that it can meaningfully be confronted with experiments. As far as we know there does not exist any theoretical or experimental argument as yet providing

unambiguous evidence for one quark charge pattern versus the other.[F15] We therefore still keep our options open regarding the nature of quark charges and await experiment to settle this question.[F15] We stress however that the twin suggestions [1,2] of quark-lepton unification and consequent baryon number violation are not tied in any way to the nature of quark charges. They are more general.]

Spontaneous versus explicit violations of B, L and F

It is now instructive to compare violations of B, L and F, which are spontaneous in origin (as outlined above) to those which are explicit. The latter arise in general if one chooses to gauge subgroups of the maximal symmetry defined by the fermion content. As mentioned earlier, examples of such subgroups are SU(5) and SO(10). For these cases, instead of the diquark current $(\bar{q}^c q)$ and (lepto-antiquark) current $(\bar{q}\ell^c)$ coupling to distinct gauge particles Y and $\bar{Y}'$, respectively, the two currents couple to one and the same gauge particle Y_s in the basic Lagrangian. This is equivalent to "squeezing" the two gauges associated with the two distinct currents mentioned above so that $Y_s \sim (Y + \bar{Y}')/\sqrt{2}$ coupling to the sum of the currents is present in the basic Lagrangian, but $Y_a \sim (Y - \bar{Y}')/\sqrt{2}$ coupling to the orthogonal combination is absent. (Equivalently, Y_a is assigned

[F15] Recent arguments of Okun, Voloshin and Zakharov (Moscow preprint ITEP-79) favouring fractional charges for quarks do not take into account the facts that (a) variation of electric charges for integer charge versus fractional charges as functions of momentum are governed by different renormalization group equations due to the presence of the colour component in the former, which is absent in the latter and (b) that for a partially confining theory there exist singularities in the variable mass parameters in time-like regions even near the origin without requiring the existence of physical particles at such points. This will be elaborated in a forthcoming preprint. A second argument based on $\eta' \to 2\gamma$ (M. Chanowitz, Phys. Rev. Letters 44, 59 (1980) favouring fractional charges is subject to the uncertain PCAC extrapolation from 1 GeV^2 to zero for the case of ICQ. There is a third argument based on an empirical analysis of deep inelastic Compton scattering $\gamma p \to \gamma + X$ data (H.K. Lee and J.K. Kim, Phys. Rev. Letters 40, 485 (1978) and J.K. Kim and H.K. Lee, preprint (1979)) which by contrast to the previous two, favours integer over fractional charges. This argument is uncertain to the extent that the P_T involved in present experiments is not high enough to permit a legitimate use of the parton model. We must wait for unambiguous experiments - like the two photon experiments in $e^+e^- \to e^+e^- +$ hadrons - to provide a definitive test. We understand that these will soon be completed.

an infinite mass.) The exchange of the Y_s particle thus leads to a violation of B, L and F in the second order of the basic gauge interactions (see Fig. 6) and induces the $\Delta F = -4$ decays

$$p \to \bar{\ell} + \text{mesons} \quad . \tag{10}$$

We see that explicit violations of B, L and F arising through squeezed gauging can in general lead to similar consequences for proton decay as the case of spontaneous violation arising for a maximal symmetry (compare Fig. 6 with Fig. 3a). To state it differently, if Y_s and Y_a are given masses in SU(16) spontaneously, in the infinite limit for the mass of Y_a, we recover the predictions of SO(10). In this sense such predictions are contained in those obtained from SU(16).

The two cases - spontaneous versus explicit violations of B, L and F - appear to possess an absolute distinction from each other at high temperatures within the range of temperatures between m_s and m_a and beyond m_a where m_s and m_a are the masses of the combinations of the fields Y_s and Y_a.

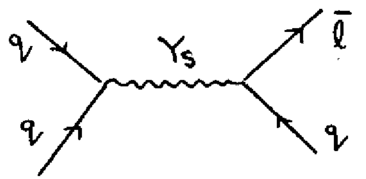


Fig. 6: Explicit violations of B, L and F through gauge squeezing. Here for example, $Y_S \equiv (Y + \bar{Y}')''/\sqrt{2}$ is a gauge particle of the basic Lagrangian but the orthogonal combination $(Y-\bar{Y}')/\sqrt{2}$ is absent or effectively has infinite mass. Such gauge squeezings occur in SU(5) and SO(10).

III. CONDITIONS FOR RELEVANCE OF ALTERNATIVE PROTON DECAY MODES

We now proceed to obtain the "necessary" and sufficient conditions for alternative proton decay modes satisfying $\Delta F = 0, -2, -4$ and -6 to be relevant for either the forthcoming or the second generation proton decay searches. For this purpose we shall consider only those mechanisms for proton decay which arise within a maximal symmetry, outlined in the previous section. Depending upon the decay modes[F16)] the experimental searches are expected to be sensitive to proton lifetimes varying between 10^{30} to 10^{33} years.

Now let us first observe the restrictions which arise from the effective low energy symmetry being $SU(2)_L \times U(1) \times SU(3)_{colour}$. Weinberg and Wilczek and Zee [19] have shown that the effective proton decay interactions based on operators of lowest dimension, which is six[F17)], automatically conserve B-L, if they are constrained to satisfy the low energy symmetry $SU(2)_L \times U(1) \times SU(3)_{colour}$. Based on this observation they have concluded that proton decay should be dominated by the $\Delta F = -4$ modes (e.g. $p \to e^+\pi^0$, $\bar{\nu}\pi^+$ etc.) which conserve B-L. In drawing this conclusion they were motivated by the assumption that the theory possesses essentially only two mass scales $m_{W_L} \sim 100$ GeV and [F18)] $M_Y \sim 10^{14} - 10^{15}$ GeV, in which case the alternative decay modes $\Delta F = 0, -2, -6$ - requiring higher dimensional operators and/or violation of $SU(2)_L \times U(1)$ - would be damped at least by a factor $\sim (m_{W_L}/M_Y)$ compared to the "allowed" (B-L) conserving decay modes in the amplitudes.

There are however good reasons why one may consider departures from this assumption.

F15) For the two-body modes such as $p \to e^+\pi^0$ and $n \to e^+\pi^-$ satisfying $\Delta F = -4$ as well as $n \to e^-\pi^+$ satisfying $\Delta F = -2$, the forthcoming experiments may be sensitive to proton lifetimes $\lesssim 10^{33}$ years. For the multiparticle modes such as $p \to e^- + 2\nu + \pi^+\pi^+$ and $n \to e^- + 2\nu + \pi^+$ satisfying $\Delta F = 0$, the sensitivity might be two or three orders of magnitude lower, while for $\Delta F = -6$ modes such as $p \to e^+ + \bar{\nu}_1 + \bar{\nu}_2$, the sensitivity may lie inbetween (see Ref. 7 for details).

F17) Thus these can include in general only operators of the form $qqq\ell$ and $qqq\bar{\ell}$ which, respectively, induce only $\Delta F = -4$ (e.g. $p \to e^+ + \pi^0$) and $\Delta F = -2$ (e.g. $p \to e^- + \pi^+\pi^+$) decays. The $\Delta F = 0$ and $\Delta F = -6$ decays would involve in any case higher dimensional operators with a minimum of six fermion fields (dimension $\gtrsim 9$).

F18) Here Y is used in the generic sense to denote a superheavy gauge particle coupling to different sorts of $F = \pm 2$ currents.

The most important is that there do exist grand unification models such as $[SU(4)]^4$, $[SU(6)]^4$ and their extended maximal versions involving fermion number gauging (such as $SU(32)$, $SU(48)$ or the smaller tribal group $[SU(16)]^3$), which do permit intermediate mass scales filling the gap between 10^2 and 10^{15} GeV with the lightest leptoquark gauge particle X as light as 10^4-10^5 GeV.[2,10] It is precisely because of the existence of these intermediate mass scales why models of Refs.2 and 9 have permitted all along alternative proton decay modes F19). This we elaborate below.

The second reason why such intermediate mass scales are worthy of consideration is purely experimental. They provide the scope for discovery of new physics through tangible evidence for quark-lepton unification in the conceivable future, especially if there exist leptoquark (X) gauge particles in the 10-100 TeV region.

The third reason is that if these intermediate mass scales do exist they would permit $\Delta F = 0$, -2 and -6 modes, whose rates may in general even exceed the rate of the $\Delta F = -4$ mode $(p \to \pi^0 + e^+)$. Experiments must therefore be designed to look for such modes.

One other reason for the existence of intermediate mass scales (with successive steps perhaps differing by powers of α or α^2) is that it may make it easier to understand the problem of the gauge hierarchy F20). And finally existence of intermediate mass scales may also account for the departure F21) of present experimental $\sin^2\theta_W \approx 0.23 \pm 0.01$ from the "canonical" theoretical value of ≈ 0.20.

F19) Several authors (Ref.20) have recently considered the possibility of intermediate mass scales permitting Higgs rather than gauge particles to acquire such masses and introducing Yukawa interactions to induce new complexions for proton decay. In view of the relative arbitrariness of Yukawa couplings we pursue the consequences which follow from the gauge interactions and the Higgs self-coupling only, subject to spontaneous symmetry breaking. Recently Weinberg has extended his analysis (Ref.21) permitting intermediate mass scales. We understand that H.A. Weldon and A. Zee (Ref.21) have made a similar analysis, though we have not seen their preprint.

F20) This is only a conjecture at present and needs to be further investigated.

F21) The weight of this remark is dependent upon further refinements in the measurements of $\sin^2\theta_W$.

With these to serve as motivations for the existence of intermediate mass scales let us first present a scenario for the hierarchy of gauge masses. This is depicted in Fig.7. We discuss later how such a scenario can be realized within maximal symmetries in accord with renormalization group equations for the gauge coupling constants. The characteristic feature of this scenario is that the leptoquark gauge particles (X) are rather light characterizing the fact that they belong to the lower sub-unification symmetry $SU(2)_L \times SU(2)_R \times SU(4)'_{L+R}$. The fermion number ±2 gauge particles Y, Y' and Y" defined already range in masses between 10^{10} and 10^{15} GeV with all possible mutual orderings including the possibility that they may all be nearly degenerate.

$F = \pm 2$	$\ell\ell$	Y"	$10^{10} - 10^{15}$ GeV
	$(q\ell)$	Y'	
	qq	Y	
$F = 0$	V+A	$W_R^\pm$	
$F = 0$	$(\bar{\ell}q)$	X's	$10^4 - 10^6$ GeV
$F = 0$	V-A	$W_L^\pm$	100 GeV
$F = 0$	photon	gluons	m = 0

Fig.7: A scenario for gauge masses arising within a maximal symmetry. The masses of Y, Y' and Y" range between 10^{10} - 10^{15} GeV with all possible mutual orderings including the possibility that they are degenerate. $W_R^\pm$ can be heavier or lighter than X's.

We now wish to argue that the $\Delta F = 0$ and -2 modes involving the decays $p \to 3\ell$ + pions and $p \to (e^-$ or $\nu)$ + pions would be relevant to forthcoming proton decay searches for the following set of values of the X and Y gauge particles:

$$\Delta F = 0 \dashrightarrow \text{Need} \quad m_X \approx 10^4 - 10^5 \text{ GeV}$$

$$\Delta F = -2 \dashrightarrow \text{Need} \quad \begin{cases} m_Y \approx 10^{10} - 10^{12} \text{ GeV} \\ m_X \approx 10^4 - 10^5 \text{ GeV} \end{cases} \qquad (11)$$

(Later we show that these requirements are met within a class of maximal symmetries.)

$\Delta F = 0$ modes ($p \to 3\ell + \pi$'s)

These decays occur for either integer or fractionally charged quarks as follows. Each quark makes a virtual transition to a lepton + a Higgs field ϕ_q^i; the three Higgs fields generated thereby combine to annihilate into vacuum through a VEV $\langle B_4^1 \rangle \neq 0$ (see Figs. 4 and 5 and discussion in the previous section). The preferred configuration corresponds to one quark being right handed, which emits a B_α^i field, and the other two being left handed, which emit appropriate components of C_α^i fields[F22]. Furthermore it turns out, owing to selection rules, that one of the quarks must proceed via a tree (Figs. 3a) and the other two via loops (Fig. 3b).[F23] The corresponding amplitudes (suppressing spinors) are given by

$$M^{L,R}_{tree}\ (\text{Fig. 3a}) = (f_X^2/m_X^2)(m_q)(\langle C_4^{*1}\rangle\ ,\ \langle B_4^{*1}\rangle)$$

$$M^{L,R}_{loop}\ (\text{Fig. 3b}) = (f_X^2/m_X^2)\left(\frac{g^2 m_q}{8\pi^2}\right)(\langle C_4^{*1}\rangle , \langle B_4^{*1}\rangle)$$
$$\times \ln(m_X^2/m^2_{W_{L,R}}) \tag{12}$$

where the superscripts L and R and the sets of parameters ($\langle C_4^{*1} \rangle$, m_{W_L}) and ($\langle B_4^{*1} \rangle$, m_{W_R}) go with the transitions of left and right-handed quarks, respectively.

F22) Recall B and C transform as $(1,2,\bar{4})$ and $(2,1,\bar{4})$ respectively under $SU(2)_L \times SU(2)_R \times SU(4)$. Together C and $B^\dagger$ make a 16 fold of SU(16). C and B fields have the same quantum numbers as the fermion fields F_L and F_R. Thus only C_4^1 and B_4^1 possess non-zero VEV, which give masses to $W_L^\pm$ and $W_R^\pm$ respectively (see Sec.II). With integer charges for quarks, additional components of C and/or B multiplets can acquire non-zero VEV (see Ref.2); but these do not materially alter the complexions of proton decay.

F23) This is under the assumption that leptoquark gauge particles (X') coupling to cross currents of the form ($\bar{e}u$) and ($\bar{\nu}d$) are much heavier than those coupling to ($\bar{\nu}u$) and ($\bar{e}d$), which are denoted by X. This situation emerges automatically if the unifying symmetry G descends to low energy symmetries via $SU(2)_L \times SU(2)_R \times SU(4)'_{L+R}$. See Ref.18 for a more general discussion.

Using these amplitudes for $q \to \ell$ + (Higgs) transitions, taking $m_X \approx (3 \text{ to } 10) \times 10^4$ GeV, and allowing a reasonable range for the Higgs parameters (which are constrained by the gauge masses, see Ref.18 for details) the proton decay rate (ignoring all but $\Delta F = 0$ modes) is found to be[18]

$$\tau_p \approx 10^{28} - 10^{34} \text{ years} \quad . \tag{13}$$

The main point worth noting is that the $\Delta F = 0$ modes become important if the leptoquark gauge boson X has a mass $\lesssim (10^4 - 10^5$ GeV). A similar mass range is also obtained in Ref.21.

$\Delta F = -2$ modes ($p \to e^-\pi^+\pi^+$ etc)

These decays arise through $X \to \Gamma$ mixing, see Fig.3b and also Sec.II). Since such a mixing violates $SU(2)_L \times U(1)$, the corresponding mixing (mass)^2 denoted by Δ^2_{XY} must be proportional to a VEV $\lesssim m_{W_L}$. Taking $\Delta^2_{XY} = m_{W_L} m_X$ (or conservatively $m^2_{W_L}$), and $m_X \approx 10^5$ GeV (as before), we see that $\Delta F = -2$ proton decay interaction viewed as an effective four fermion interaction would have a strength $(\Delta^2_{XY})/(m_X^2\, m_Y^2)$. This would exceed the canonical value $\approx 10^{-29}$ GeV^{-2} for $m_Y \approx 10^{13}$ GeV (or 3×10^{11} GeV), leading to proton lifetime in the range of $10^{31} - 10^{32}$ years.

We thus see that for $m_X \approx 10^4 - 10^5$ GeV and $m_Y \approx 3\times 10^{11} - 10^{13}$ GeV (the precise number depending upon Δ^2_{XY}), <u>$\Delta F = 0$ as well as $\Delta F = -2$ could coexist</u> with comparable rates and be relevant to forthcoming proton decay searches.

<u>$\Delta F = -4$ modes ($p \to e^+\pi^0$ etc)</u>

These arise through $Y \leftrightarrow \bar{Y}'$ mass mixing (see Fig.3a). Denoting the mixing (mass)^2 by $\Delta^2_{YY'}$, the corresponding amplitude is $\Delta^2_{YY'}/(m_Y^2 \sim m_{Y'}^2)$. As explained in Sec.II, $\Delta^2_{YY'}$ can be as large as $m_Y^2 \sim m_{Y'}^2$. This is the case for example if SU(16) descends to low energy symmetries without passing through SU(8) × SU(8) × U(1). If $\Delta^2_{YY'}$ has its maximum value $m_Y^2 \approx m_{Y'}^2$ (as in the case for example for SO(10)), then the $\Delta F = -4$ amplitude would have a strength $\approx 1/m_Y^2$ and a proton lifetime $\approx 10^{30}$ years would require $m_Y \approx 10^{14}$ GeV. However, with the perfectly feasible possibility of $\Delta^2_{YY'}$ smaller than m_Y^2, there is the possibility that proton lifetime of 10^{30} years can be compatible with Y and Y' being lighter. For example if $\Delta^2_{YY'} = (10^{10}\ \text{GeV})^2$ then proton lifetime of 10^{30} years would be compatible with $m_Y \approx m_Y' \sim 10^{12}$ GeV. We are interested in this possibility because for such values of Y mass (and with $m_X \approx 10^4 - 10^5$ GeV), the $\Delta F = -2$ and the $\Delta F = 0$ modes become relevant as well. Thus we see that a gauge mass pattern

$$m_X \sim 10^4 - 10^5\ \text{GeV},\quad m_Y \approx m_{Y'} \approx 10^{12}\ \text{GeV}, \tag{14}$$

$$(\Delta^2_{YY'})^{1/2} \approx 10^{10}\ \text{GeV and } (\Delta^2_{XY})^{1/2} \approx m_{W_L} m_X \tag{15}$$

would permit the possibility that $\Delta F = 0$, -2 <u>and</u> -4 modes can co-exist and be relevant to present searches. The possible co-existence of the $\Delta F = -6$ mode depends upon some further considerations which we shall not pursue here.

Our task now is to show that such mass patterns as outlined in (15) can be realized within unifying symmetries in accord with renormalization group equations as well as observed values of $\sin^2\theta_W$ and α_S.

IV. SOLUTIONS TO HIERARCHY EQUATIONS FOR A CLASS OF UNIFYING SYMMETRIES

Perturbative renormalization group equations for the running coupling constants of a spontaneously broken unifying symmetry permit in general solutions for the gauge masses [6], which exhibit a hierarchy. We refer to these equations as hierarchy equations and ask: Do there exist solutions to these equations within some class of unifying symmetries which permit

$$\begin{aligned}
&\text{(a)}\quad M_X \sim 10^4 - 10^5\ \text{GeV}\\
&\text{(b)}\quad M_Y \sim 10^{11} - 10^{15}\ \text{GeV}\\
&\text{(c)}\quad \sin^2\theta_W \approx 0.23 \quad\text{and}\\
&\text{(d)}\quad \alpha_S(m_W) \approx 0.14.
\end{aligned} \tag{16}$$

We know that the answer is negative for SU(5) and SO(10).

Now to see how a "light" leptoquark gauge particle X with a mass $\approx 10^4 - 10^5$ GeV can be realized in the first place, it is instructive to recall the case of the two-family $[SU(4)]^4$ model, which possesses a single gauge coupling constant because of discrete symmetry between the four SU(4) factors. This symmetry depending upon the nature of SSB can break via two alternative chains

$$[SU(4)]^4 \begin{cases} \xrightarrow{M_1} SU(2)_L^{I+II} \times U(1) \times SU(3)'_{L+R} \\[2ex] \xrightarrow[M_1]{} SU(2)_L^{I+II} \times U(1) \times SU(3)'_L \times SU(3)'_R \end{cases} \tag{17}$$

Here $SU(4)^{\text{flavour}}_{L,R}$ acts on $(u,d,c,s)_{L,R}$ flavours. $SU(2)^I_L$ and $SU(2)^{II}_L$ act on $(u,d)_L$ and $(c,s)_L$ doublets respectively; $SU(2)^{I+II}_L$ is their diagonal sum. The gauge particles of $SU(2)^{I+II}_L$

are related to those of $SU(2)_L^{I,II}$ by $W_L^{I+II} = (W_L^I + W_L^{II})/\sqrt{2}$. Thus, if g is the symmetric gauge coupling constant of each SU(4) factor, the coupling constant g_2 of the low energy symmetry $SU(2)_L^{I+II}$ would approach $g/\sqrt{2}$ in the symmetry limit. Likewise the coupling constant g_3^V for vector colour $SU(3)_{L+R}$ would also approach $g/\sqrt{2}$, since it is obtained by diagonal summing of $SU(3)'_L$ and $SU(3)'_R$. By contrast the coupling constant g_3^c for chiral colour [F24] $SU(3)'_L \times SU(3)_R$ (relevant to the lower chain) would approach g in the symmetric limit. Thus

$$\text{vector colour} \quad g_2 = g_3^V = \frac{g}{\sqrt{2}} \quad \text{(symmetric limit)}$$

$$\text{chiral colour} \quad g_2 = \frac{g}{\sqrt{2}}\ ;\ g_3^c = g \ \text{(symmetric limit)} \tag{18}$$

It can be shown that this difference of a factor of $1/\sqrt{2}$ between flavour versus colour coupling constants, translates into a factor ≈2.5, which multiplies the logarithm of M_1/μ. It alters drastically the determination of the unification mass M_1 and one obtains [10]

$$\text{For vector colour} \begin{cases} M_1 \approx 10^{15}\ \text{GeV} \\ \sin^2\theta_W \approx 0.20 \end{cases}$$

$$\text{For chiral colour} \begin{cases} M_1 \approx 10^6\ \text{GeV} \\ \sin^2\theta_W = \frac{2}{7} + \frac{10}{21\alpha_s} \approx 0.30 \end{cases} \tag{19}$$

The mass of X is about a factor of 10 lower than M_1. Thus for $M_1 \approx 10^6$ GeV, m_X is $\approx 10^5$ GeV, as desired. However the case of the two family $[SU(4)]^4$ descending via chiral colour is now excluded experimentally, since it yields too high a value for $\sin^2\theta_W$ ($\simeq 0.30$) compared to the experimental value of ≈ 0.23.

Nevertheless the above example provides the clue for low mass unification. The idea is to create through spontaneous descent a dichotomy between low energy flavour versus colour coupling constants such that the former is lower than the latter in the

F24) The chiral colour symmetry must break to vectorial colour eventually. But if this breaking takes place by a mass scale < m_{W_L}, one can ignore the effect of such a breaking for studies of renormalization group equations at momenta m_{W_L}.

symmetric limit. [F25] This is best illustrated by the three family symmetry [22] $[SU(6)]^4$, which operators on six flavours (u,d,c,s,t,b) and six colours. There are three leptonic colours rhyming with three quark colours (r,y and b). There are the six observed leptons plus twelve unobserved heavy leptons in the model. [F26] Here the low energy flavour $SU(2)_L$ is obtained by diagonal summing of three SU(2)'s, which respectively act on (u,d), (c,s) and (t,b) - doublets. Thus $g_2 = g/\sqrt{3}$ in the symmetric limit. In this case, even if the low energy colour symmetry is vectorial $SU(3)'_{L+R}$, $g_2 = g/\sqrt{3} < g_3^V = \frac{g}{\sqrt{2}}$ in the symmetric limit. This, together with the fact that the bare value of the weak angle [23] $\sin^2\theta_0 = 9/28$ (rather than 3/8), leads again to a low unification mass for the descent $[SU(6)]^4 \xrightarrow{M_1} SU(2)_L^{I+II+III} \times U(1) \times SU(3)'_{L+R}$, i.e.

$$M_1 \approx 10^6\ \text{GeV, i.e. } m_X \approx 10^5\ \text{GeV.} \tag{20}$$

In this case one furthermore obtains a desirable value for the weak angle [23]

$$\sin^2\theta_W = \frac{5}{24} + \frac{19}{36}\frac{\alpha}{\alpha_s} \approx 0.235 \quad . \tag{21}$$

We thus see that quark-lepton unification could take place through leptoquark gauge interactions at an energy scale 10^5 GeV. For the chiral descent $[SU(6)]^4 \to SU(2)_L^{I+II+III} \times U(1) \times SU'_L(3) \times SU'_R(3)$ the unification mass could be lower still ($\approx 10^4$ GeV).

What about the masses of the fermion number F = ±2 gauge particles Y, Y' and Y" arising within a maximal symmetry? To obtain a scenario in which the masses of these gauge particles lie in the range of $10^{10} - 10^{15}$ GeV, while the X's are as light as $\approx 10^4$-10^5 GeV, we proceed as follows. [F27] Assume (following the

F25) This ingredient hastens the "meeting" of the colour and the SU(2) flavour coupling constants. There is a second ingredient which can speed up the "meeting" of SU(2) and U(1) coupling constants. This is realized through a lowering of the bare value of the weak angle $\sin^2\theta_0$ from the canonical value 3/8. This is the case for $[SU(6)]^4$ where $\sin^2\theta_0 = \frac{9}{28}$ on account of the presence of the extra leptons. However for SU(16) or $[SU(16)]^3$, $\sin^2\theta_0$ has the "canonical" value $\frac{3}{8}$.

F26) This is without counting the mirror fermions.

F27) The discussions to follow are based on a forthcoming paper by B. Deo, J.C. Pati, S. Rajpoot and Abdus Salam (Ref.24).

illustrations for $[SU(4)]^4$ and $[(SU(6)]^4)$ that each individual family defines a distinct SU(2) within the parent symmetry G; these distinct SU(2)'s combine (or following a terminology used before, they are "squeezed") through spontaneous symmetry breaking by a relatively heavy ~~mass scale~~ [F28] M_L to yield the diagonally summed SU(2), which is the SU(2) of low energy electroweak symmetry. Thus allowing for q left-handed families we envisage the descent

$$[SU(2)_L]^q \xrightarrow[SSB]{M_L} SU(2)_L \,. \tag{22}$$

Recall that for $[SU(4)]^4$, $q = 2$, while for $[SU(6)]^4$, $q = 3$. If the theory is left-right symmetric, there would be the corresponding "squeezing of $[SU(2)_R]^q$ into a single $SU(2)_R$ or even $U(1)_R$ through a heavy mass scale M_R

$$[SU(2)_R]^q \xrightarrow{M_R} SU(2)_R \text{ or } U(1)_R \,. \tag{23}$$

In general the parent symmetry G may contain distinct SU(4) colour symmetries [F29] as well, which are distinguished from each other either through helicity of fermions on which they operate, or through the family attribute, or both. For generality assume that there are p SU(4) colour symmetries within G. To be specific we shall furthermore assume that these are vectorial L+R symmetries. (The generalization to chiral SU(4) colour is straightforward.) [F30] These p $SU(4)_{L+R}$ symmetries are "squeezed" through SSB to a single $SU(4)_{L+R}$ by a heavy mass scale M_4. The single $SU(4)_{L+R}$ subsequently descends also spontaneously to $SU(3)^{colour}_{L+R} \times U(1)_{L+R}$ via a heavy mass scale M_3. The leptoquark gauge particles X's receive their mass through M_3 with $M_X \approx M_3/10$. Thus the colour sector may break as follows:

$$[SU(4)_{L+R}]^p \xrightarrow{M_4} SU(4)_{L+R} \xrightarrow{M_3} SU(3)_{L+R} \times U(1)_{L+R} \,. \tag{24}$$

F28) To realize the known universality of different families in electroweak interactions and to preserve the GIM mechanism upto its known accuracy M_L should exceed about 10^5 GeV.

F29) The fourth colour is lepton number.

F30) Alternatively $[SU(4)]^p$ may descend first to $[SU(3)]^p \times [U(1)]^p$, which subsequently descends to $[SU(3)] \times U(1)$. This is considered in Ref.24.

In short the scenario which we are led to consider for the sake of obtaining intermediate mass scales and thereby signals for grand unification at moderate energies is this: The families define distinct SU(2)'s and possibly even distinct SU(3) or SU(4) colour symmetries at the level of the parent symmetry. The distinction is lost and thereby universality of families defined by discrete symmetries $e \leftrightarrow \mu \leftrightarrow \tau$ emerges at low energies due to spontaneous symmetry breaking. F31)

Such family distinctions are not realized within smaller symmetries such as SU(5), SO(10) and SU(16). But they do exist within symmetries such as $[SU(4)]^4$, $[SU(6)]^4$, $[SU(5)]^3 = SU(5)_e \times SU(5)_\mu \times SU(5)_\tau \subset SU(15)$ and likewise $[SO(10)]^3$ and $[SU(16)]^3 \subset SU(48)$.

We are aware that the symmetries of the latter kind are gigantic. But then Nature appears to be proliferated anyway beyond one's imagination at the quark-lepton level. Why are there families at all? If families proliferate, why not the gauge mesons? At the present stage of our ignorance there is no basic reason why the family universality should be an exact principle for all energies. The gigantic symmetries are the price one is paying for believing quarks and leptons are fundamental entities. We return to this problem towards the end.

With these remarks to serve as motivations, we consider the possibility that the parent symmetry G breaks spontaneously to low energy components as follows: 24

F31) For instance, taking only two families e and μ, there are two distinct W's (W_e and W_μ) in the basic Lagrangian. Due to hierarchical SSB $(W_e - W_\mu)/\sqrt{2}$ acquires a heavy mass $\gtrsim 10^5$ GeV, but $(W_e + W_\mu)/\sqrt{2}$ acquires a mass only of order 100 GeV. Hence the low energy $e \longleftrightarrow \mu$ universality. Such a picture is logically feasible, since tests of $e \longleftrightarrow \mu$ universality in weak interactions extend at best upto 10 to 30 GeV of centre-of-mass energies. <u>Do there exist additional W's and Z's which couple to differences of e and μ currents?</u> Tests of such family universality should provide an important motivation for building high energy accelerators in the 1-100 TeV region.

$$\begin{array}{ccccccc} G \xrightarrow{M} & [SU(2)_L]^q & \times & [SU(2)_R]^q & \times & [SU(4)_{L+R}]^p & \times\, U(1) \\ & \downarrow{\scriptstyle M_L} & & \downarrow{\scriptstyle M_R} & & \downarrow{\scriptstyle M_4} & \\ & SU(2)_L & & U(1)_R & & SU(4)_{L+R} & \\ & & & & & \downarrow{\scriptstyle M_3} & \\ & & & & & SU(3)_{L+R}\times U(1)_{L+R} & \\ & & & \downarrow{\scriptstyle m_{W_L}} & & & \\ & & & SU(2)_L \times U(1) \times SU(3)_{L+R} & & & \end{array} \qquad (25)$$

Such a hierarchy leads to the following two equations via the renormalization group equations for the coupling constants:

$$\frac{\sin^2\theta_0 - \sin^2\theta_W}{\alpha \cos^2\theta_0} = -\frac{11 \ln_e A}{6\pi \cos^2\theta_0} \xrightarrow[M]{\text{Single}} \frac{11}{3\pi} \ln\frac{M}{\mu}$$

$$\frac{q}{\alpha_S} - \frac{p}{\alpha}\sin^2\theta_W = -\frac{11 \ln B}{6\pi} \xrightarrow[M]{\text{Single}} -\left(\frac{3q-2p}{2}\right)\frac{11}{3\pi}\ln\frac{M}{\mu}$$

$$A \equiv D^{-1}\left[\left(\frac{M}{M_L}\right)^{2q}\left(\frac{M_L}{m_{W_L}}\right)^{2}\left(\frac{M}{M_R}\right)^{2q}\left(\frac{M}{M_4}\right)^{\frac{8p}{3}}\left(\frac{M_4}{M_3}\right)^{\frac{8}{3}}\right]^{\sin^2\theta}$$

$$B \equiv D^{-1}\left[\left(\frac{M}{M_4}\right)^{4p}\left(\frac{M_4}{M_3}\right)^{4}\left(\frac{M_3}{m_{W_L}}\right)^{3}\right]$$

$$D = \left(\frac{M}{M_L}\right)^{2q}\left(\frac{M_L}{m_{W_L}}\right)^{2} \qquad (26)$$

The reductions shown on the right sides of the two top equations correspond to a single stage descent $G \xrightarrow{M} SU(2)_L \times U(1) \times SU(3)_{L+R}$ for which $M_L = M_R = M_4 = M_3 = M \gg m_{W_L}$.

We now ask, are there solutions to these equations for some p and q which correspond to the constraints on gauge masses as well as $\sin^2\theta_W$ and α_S as listed in the relation (16)? (Note that chiral colour corresponds to p = 2.) We find [24] that there is no solution satisfying constraint (16) for p = q = 1; such values of p and q correspond to SU(5) and SO(10). There is also no solution for p = 2, q = 1 which correspond to SU(16). But there do exist solutions for p = q = 2; for p = 2, q = 3 and for p = q = 3. Such values of p and q can be obtained for example within $[SO(10)]^3$, $[SU(16)]^3$. These solutions and the corresponding coexistence of alternative proton decay modes are listed below:

$$p = q = 2 \quad \begin{cases} M \sim 10^{15}\ \text{GeV},\ M_4 \sim M_L \sim M_R \sim 10^{12}\ \text{GeV} \\ M_3 \sim 10^{5.5}\ \text{GeV} \Rightarrow M_X \sim 10^{4.5}\ \text{GeV} \\ \text{Thus } \Delta F = 0 \text{ and } \Delta F = -4 \text{ can coexist, but} \\ \Delta F = -2 \text{ is suppressed} \end{cases}$$

$$p = 2,\ q = 3 \quad \begin{cases} M \approx M_4 \approx 10^{12}\ \text{GeV},\ M_R \approx 10^{10}\ \text{GeV} \\ M_L \approx 10^{7}\ \text{GeV},\ M_3 \approx 10^{5}\ \text{GeV} \Rightarrow M_X \sim 10^{4}\ \text{GeV} \\ \Delta F = 0,\ -2 \ \underline{\text{and}}\ -4 \text{ can coexist} \end{cases}$$

$$p = q = 3 \quad \begin{cases} M \approx M_R \sim 10^{12}\ \text{GeV},\ M_4 \approx 10^{9}\ \text{GeV},\ M_L \approx 10^{6}\ \text{GeV} \\ M_3 \approx 10^{5}\ \text{GeV} \Rightarrow M_X \sim 10^{4}\ \text{GeV} \\ \Delta F = 0,\ -2 \ \underline{\text{and}}\ -4 \text{ can coexist} \end{cases} \qquad (27)$$

We thus see that within maximal symmetries permitting intrinsic family distinctions proton can decay through alternative decay modes as claimed in the introduction.F32) It is also worth noting that for three families with p = q = 3, the family universality of weak interactions can disappear at an energy scale of order 100 TeV corresponding to $M_L \approx 10^6$ GeV.

F32) Recently, Weinberg (Ref.21) has noted that in addition to the $\Delta(B-L) = 0$, $\Delta F = -4$ mode ($p \to e^+\pi^0$) there can be only one other proton decay mode satisfying either $\Delta F = 0$, $\Delta F = -2$, or $\Delta F = -6$. He was led to this observation by arguing that the $\Delta F = 0$, -2 or -6 processes, which are mediated by intermediate mass scales $M_I \ll M \sim 10^{14}$ GeV would have rates $\sim \alpha T$ or $\alpha^2 T$ in the early Universe at temperatures in the range $M \gg T \gg M_I$. Such processes with rates exceeding the rate of expansion of the Universe would be in thermal equilibrium and therefore wipe out any baryon excess generated in earlier epochs (due to $\Delta F = -4$ processes), unless a specific linear combination $(B + aL)$ is absolutely conserved. We observe that these arguments apply only if B, L, F violations are explicit rather than spontaneous. For the latter case, the violations disappear for temperatures $T > M_I$. Thus any baryon excess generated before this epoch is not wiped out. Thus there is no conflict between coexistence of $\Delta F = 0$, -2 and -4 modes for proton decay on the one hand and the observation of baryon excess on the other, if the violations are spontaneous.

V. A SUMMARY OF THE FIRST PART

We raised two questions:

(i) Is it conceivable that the basic idea of quark-lepton unification may be tested tangibly through manifestation of exotic quark-lepton interactions in the conceivable future? This has been answered in the affirmative. A number of unification models permit at least the leptoquark X gauge particles to possess a mass in the 10-100 TeV region. We need Isabelle, ISR and their immediate successors thereof as well as improved cosmic ray studies to see the effects of the X particle. These may be seen for example through enhanced lepton pair production in pp and $\bar{p}p$ processes.

(ii) Can the variety of complexions for proton decay outlined in Sec.I exist and coexist? This question has also been answered.

To summarise:

(1) The idea of quark-lepton unification is not tied to the nature of quark charges.

(2) Proton decay is central to the hypothesis of quark lepton unification. It is a reasonable expectation within most models that the lifetime of the proton should lie within the range of $10^{28} - 10^{33}$ years.

(3) Proton decay modes can provide an important clue to the underlying design of grand unification. For example, observation of $\Delta F = 0$, -2 or -6 mode at any level within the conceivable future will signal the existence of intermediate mass scales, which in turn will reflect upon the nature of the parent symmetry G. In particular, the observation of the $\Delta F = 0$ mode will strongly suggest the existence of new interactions in the 10 to 100 TeV region. Thus, a search for such decay modes, if need be through second and third *generation experiments, would be extremely important in* that such searches would have implications for building of high energy accelerators.

(4) Observation of proton decay will strongly support the idea that quark and leptonic matters are ultimately of the same kind, though this has no bearing on the question of whether quarks and leptons represent the ultimate constituents of matter.

This leads to the second part of our considerations where we indicate the directions in which some of the changes might occur for the unification hypothesis, if quarks and leptons are viewed as composites of more elementary objects - the preons, and also how the preons may bind.

VI. PREONS F33)

To resolve the dilemma of quark-lepton proliferation it was suggested in 1974 that quarks and leptons may define only a stage in one's quest for elementarity [26,27]. The fundamental entities may more appropriately correspond to the truly fundamental "attributes"(charges) exhibited (or yet to be exhibited) by Nature. The fields carrying these fundamental attributes we called "PREONS". Quarks and leptons F34) may be viewed within this picture as composites of a set of preons consisting, for example, of m elementary "flavons" (f_i) plus n elementary "chromons" (C_α). The flavons carry only flavour but no colour, while the chromons carry only colour but no flavour. If both flavons and chromons carry spin-½, one needs to include a third kind of spin-½ atrribute (or attributes) in the preon-set, which for convenience we shall call F35) "spinons" (ζ_ν); these serve to give spin-½ to quarks and leptons but may in general serve additional purposes. The quarks and leptons are in the simplest case composites of one flavon, one chromon and one spinon plus the "sea". If the μ and τ families are viewed to differ from the e-family only in respect of an "excitation quantum number" or degeneracy quantum number, which is lifted by some "fine or hyperfine" interaction, then only seven preons consisting of (u,d,r,y,b,ℓ and ζ) suffice to describe the 24 quarks and leptons of 3 families (and possibly others yet to be discovered).

For this reason, the preon idea appears to be attractive. But can it be sustained dynamically? The single most important problem which confronts the preon-hypothesis is this: What is the nature and what is the origin of the force which binds the preons to make quarks and leptons?

Our first observation, following the work of one of us [25], is that ordinary "electric" type forces F36) - abelian or non-abelian - arising within the grand

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F33) This section follows a recent paper by J.C. Pati (Ref.25). See also remarks by Abdus Salam, Concluding talk, EPS Conference, Geneva, 1979.

F34) For simplicity let us proceed with the notion that lepton number is the fourth colour (Ref.2). In this case the composite structure is as follows: $(q_u)_{r,y,b} = u + (r,y \text{ or } b) + \zeta$, while $\nu = u + \ell + \zeta$ etc. Withinin the preon-idea leptons may however differ from quarks by more than one attribute. For example, we may have $\nu = u + \ell + \zeta'$ where ($\zeta' \neq \zeta$). Such variants will be considered elsewhere.

F35) With the spinon present the flavons and chromons can carry integer spin 0 or 1.

F36) By "electric" type forces we mean forces whose effective coupling strength is of order $\alpha \gtrsim 1/137$ at the unification point M.

unification hypothesis are inadequate to bind preons to make quarks and leptons unless we proliferate preons much beyond the level depicted above.

The argument goes as follows: Since quarks and leptons are point-like - their sizes are smaller than 10^{-16} cm as evidenced (especially for leptons) by the (g-2) experiments - it follows that the preon binding force F_b must be strong or superstrong at short distances $r \lesssim 10^{-17} - 10^{-18}$ cm corresponding to running momenta $Q \gtrsim 1$ to 10 TeV. (Recall for comparison that the chromodynamic forces generated by the $SU(3)_{colour}$-symmetry is strong ($\alpha_c \gtrsim 1$) only at distances of order 1 Fermi, which correspond to the sizes of the known hadrons.) This says that the symmetry generating the preon binding force must lie outside of the familiar $SU(2) \times U(1) \times SU(3)_{col}$ symmetry.

Now consistent with our desire to adhere to the grand unification hypothesis, we shall assume that the preon binding force F_b derives its origin either intrinsically or through the spontaneous breakdown of a grand unifying symmetry G. Thus either the basic symmetry G is of the form $G_k \times G_b$ with G_k generating the known electroweak-strong forces and G_b generating the preon-binding forces, (in this case G_k and G_b are related to each other by a discrete symmetry so as to permit a single gauge coupling constant); or the unifying symmetry G breaks spontaneously as follows:

$$G \xrightarrow{SSB} G_k \times G_b \times [\text{possible } U(1)\text{-factors}] \; . \tag{28}$$

In the second case G_k need not be related to G_b by discrete symmetry. But in either case G_k contains the familiar $SU(2)_L \times U(1)_{EW} \times SU(3)_{colour}$-symmetry and therefore the number of attributes (N_k) on which G_k operates needs to be at least 5. This corresponds to having 2 flavons (u,d) plus three chromons (r,y,b). To incorporate leptonic chromon ℓ and possibly also the spinon ζ, N_k may need to be at least 7; but for the present we shall take conservatively $N_k \geqslant 5$.

Now consider the size[F37] of G_b. On the one hand the effective coupling constant $\bar{g}_b$ of the binding symmetry G_b is equal to the effective coupling constant $\bar{g}_c$ of the familiar SU(3)-colour symmetry (up to embedding factors [10] like $1/\sqrt{2}$ or $1/\sqrt{3}$ etc.) at the unification mass scale $M >> 10^4$ GeV. On the other hand, $\bar{\alpha}_b \equiv \bar{g}_b^2/4\pi$ needs to exceed unity at a momentum scale $\mu_b \gtrsim 1$ to 10 TeV, where the chromodynamic coupling constant $\bar{\alpha}_c << 1$. It therefore follows (assuming that the embedding factor mentioned

F37) In these considerations we assume all along that the conventional perturbative renormalization group approach applies to the variations of all running coupling constants down to such momenta, where they are small ($g_i^2/4\pi \lesssim 0.3$) (see Ref.6).

above is unity) that G_b is much larger than SU(3).[F38] Using renormalization group equations for variations of the coupling constants $\bar{\alpha}_b$ and $\bar{\alpha}_c$, one may verify that G_b minimally is SU(5) and correspondingly the dimension N_b of the space on which G_b operates is minimally 5.

Now the preons $\{P_i\}$ which bind to make quarks and leptons must be non-trivial with respect to both G_k and G_b. Since each of G_k and G_b requires for their operations a space, which is minimally five dimensional, it follows that the number of preons N_p needed (under the hypothesis above) is mainly $N_k \times N_b \geqslant 25$.

$$N_p \geqslant N_k \times N_b \geqslant 5 \times 5 = 25 \; . \tag{29}$$

We may consider relaxing the assumption that the emebedding factor is unity. This would permit the ratio $[\bar{g}_b(\mu)/\bar{g}_c(\mu)]_{\mu=M}$ to be a number like $\sqrt{2}$ or $\sqrt{3}$ for example. In turn this can result in a reduction in the size of G_b. But simultaneosuly such a step necessitates an increase in the size of G_k or effectively of the number N_k with the result that the minimal number of preons needed $N_p \geqslant N_k \times N_b$ is not reduced below 21.

This number 25 (or 21) representing the minimal number of preons needed already exceeds or is close to the number of quarks and leptons which we need at present, which is 24. And if we include, more desirably, the leptonic chromon ℓ and the spinon ζ in the preonic degrees of freedom, the number of preons needed would increase to 35 (or 27).

Such a proliferation of preons defeats from the start the very purpose for which they were introduced - economy. In turn, this poses a serious dilemma. On the one hand giving up the preon idea altogether and living with the quark-lepton system as elementary runs counter to one's notion of elementarity and is thus unpalatable. On the other hand, giving up the grand-unification hypothesis is not aesthetically appealing.

Because of this impasse, it has recently been suggested [25] that the preons carry not only electric but also magnetic charges and that their binding force is magnetic in nature. The two types of charges are related to each other by the familiar Dirac-like quantization conditions [28,29] for charge-monopole or dyon systems, which imply that the magnetic coupling strength $\alpha_m \equiv g_m^2/4\pi$ is $O(1/\alpha_e) \approx O(137)$ and thus is superstrong. In other words, the magnetic force can

F38) This incidentally excludes the possibility that G_b is abelian.

arise through an abelian U(1)-component within the unification hypothesis (as remarked further at the end) and yet it can be superstrong. This is what gives it the power to bind preons into systems of small size without requiring a proliferation. Quarks and leptons do not exhibit this superstrong force because they are magnetically neutral (see remarks below).

We first discuss the consistency of this idea with presently known phenomena from a qualitative point of view and later indicate the possible origin of this magnetic force.

(1) Since the electric fine structure constant $\alpha_e = e^2/4\pi$ varying with running momentum remains small $\approx 10^{-2}$ almost everywhere (at least up to momenta $\sim 10^{14}$ GeV and therefore up to distances $\sim 10^{-28}$ cm), the magnetic "fine structure" constant $\alpha_m \equiv g^2/4\pi$ related to α_e by the reciprocity relations is superstrong even at distances as short as 10^{-28} cm (if not at $r \to 0$). It is this strong short distance-component of the magnetic force, which makes quarks and leptons so point-like with sizes $r_0 << 10^{-16}$cm. Their precise size would depend upon the dynamics of the superstrong force which we are not yet equipped to handle. For our purposes we shall take r_0 to be as short as perhaps $1/M_{Planck} \sim 10^{-33}$ cm but as large as perhaps 10^{-18} cm (i.e. $r_0 < 10^{-18}$ cm).

(2) Quarks and leptons do not exhibit even a trace of the superstrong interactions of their constituents because they are magnetically neutral composites of preons and their sizes are small compared to the distances $R \gtrsim 10^{-16}$ cms which are probed by present high energy experiments.

(3) We mention in passing that had we assumed, following Schwinger [29], that quarks (rather than preons) carry magnetic charges, we would not understand why they interact so weakly at short distances as revealed by deep inelastic ep-scattering.

(4) Due to their extraordinarily small sizes, it can also be argued [25] that low energy parameters such as (g-2) of leptons would not show any noticeable departures from the normal expectations. Similar remark applies to the P and T violations for quarks and leptons, which would be severely damped in spite of large P and T violations for preons carrying electric and magnetic charges.

What can be the possible origin of magnetic charges of preons? The origin could perhaps be topological [30,31]. Spontaneous breaking of the non-abelian preonic local symmetry G_p to lower symmetries may generate monopoles or dyons. Such a picture would be attractive if in particular it could generate spin ½ monopoles (in addition to spin 0 and spin 1) and assign electric and magnetic charges to the originally introduced spin ½ fields and their topological counterparts.

There is a second alternative, which is the simplest of all in respect of its gauge structure. Assume that the basic Lagrangian of the preons is generated simply by the abelian symmetry $U(1)_E \times U(1)_M$. The $U(1)_E$ generates "electric" and $U(1)_M$ the "magnetic" interactions of preons. Subject to subsidiary conditions. the theory generates only one photon coupled to electric as well as magnetic charges [32]. The charges are constrained by the Dirac quantization condition. <u>In this model the basic fields are only the spin ½ preons and the spin-1 photon.</u> The strong magnetic force binds preons to make spin ½ quarks and leptons as discussed earlier. Simultaneously it makes spin-1 and spin-0 composites of even number of preons (including antipreons), which also have very small sizes like the quarks and leptons. The spin-0 and spin-1 fields carry charges and interact with quarks and leptons as well as among themselves. The use of a recently suggested "theorem" [33] would then suggest that their effective interactions must be generated from a local non-abelian symmetry of the Yang-Mills type, which is broken spontaneously, in order that they may be renormalizable. The spin-0 composites will now play the role of Higgs-fields.[34] It is amusing that if this picture can be sustained, the proliferated non-abelian quark-lepton gauge structure $G_{(q,\ell)}$ with the associated spin ½, spin-1 as well as spin-0 quanta may have its origin in the simplest interaction of all: electromagnetism defined by the abelian symmetry $G_P = U(1)_E \times U(1)_M$.

The idea of the magnetic binding of preons and its origin needs to be further developed. What is argued here is that within the unification context a magnetic binding of preons appears to be called for if we are not to proliferate preons unduly.

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