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LEPTON-HADRON UNIFICATION

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ABSTRACT

Four unconfined leptons and twelve integer-charged quarks are united in a single fermionic multiplet of $SU(4)|_{flavour} \times SU(4)|_{colour}$. The coloured gauge 1^- particles give strong interactions. The distinction between leptonic and quark interactions is expected to disappear beyond characteristic energies of the order of 10^5 GeV (input $K^0 \to e + \mu$ decay branching ratio). There are three distinguishing tests for the theory:

1) σ_L/σ_T in eN and μN is $\neq 0$ and scales in x.

2) Strong coloured vector gluons $V^{\pm}$ mix with $W^{\pm}$, leading to copious leptonic decays of $V^{\pm}$ (branching ratio $\geqslant 40\%$). In semi-leptonic decays of $V^{\pm}$, K, π and η's are produced in pairs and not singly.

3) Most characteristic of all, we predict quark decays into leptons with violation of baryon and lepton numbers. Besides conventional charm mesons and baryons, decaying quarks and charged colour gluons provide new sources of multi-leptons for e^-e^+, νN, eN, μN and NN collisions. The expected dissociation of nucleons into quarks in ℓN and NN collisions at high energies and the subsequent decay of single quarks into leptons (but not antileptons) implies a deviation of leptonic/anti-leptonic ratio fundamentally different from unity.

4) As a characteristic result, we expect $\mu^-\mu^-$ in νN but no $\mu^+\mu^+$ in $\bar{\nu}$N or trimuons so far as the dissociation mechanism is concerned.

I. INTRODUCTION

Leptons and hadrons share equally three of the basic forces of nature: electromagnetic, weak and gravitational. The only force which is supposed to distinguish between them is strong. Could it be that leptons share with hadrons this force also, and that there is just one form of matter [1], not two?

The idea would have sounded fantastic a few years ago. That it does not do so today is due to the discovery of the neutral currents together with the expectation that this implies a gauge unification of weak and electromagnetic forces - and, in particular, the expectation that the neutrino is now no longer the, humble, only feebly interacting particle, with none but weak couplings. Our present view is that the neutrino interactions are most likely of basic electromagnetic strength (order α); only that this strength does not manifest itself for presently attained laboratory energies. For experiments involving energies and momentum transfers much exceeding $(\alpha\, G_F^{-1})^{1/2} \approx 50$ GeV, neutrinos will interact with their full strength (α) with matter.

The lepton-hadron unification hypothesis would maintain that a similar expectation can be entertained for all leptons in the context of strong interactions also. Leptons exhibit no strong interactions at presently attained energies. They may, however, do so at higher energies and momentum transfers, thereby removing the last distinction between leptons and hadrons [2].

In 1972, when these ideas were first stated [1], they were heresy. Today we do not think there is any gauge theorist who will disagree with them. The only area of dispute can be about the characteristic energy when this unification may manifest itself. In 1972 we suggested that this characteristic energy may be around 10^5 GeV. We fixed on this from the internal consistency of the gauge theory we had constructed - the input being the branching ratio of $K^0 \rightarrow e^- + \mu^+$ decay. Since then we have been attempting to modify our model so that it would permit of a characteristic energy lower still. Other theorists have argued that the energy in question should be at least as high as 10^{19} GeV - the so-called Planck energy given by the square root of Newtonian constant G_N, at which the gravitational effects also become important. In these lectures we shall stick to the earlier estimate of our "basic model" and make deductions therefrom. Unfortunately, even 10^5 GeV (in centre of mass) is the energy of the highest cosmic rays, and possibly unattainable in the laboratory at any foreseeable future.

The basic assumptions we shall make are the following:

(1) Leptons and quarks are both elementary entities for gauge theory purposes. If leptons are composite, $(g-2)_{e,\mu}$ experiments, and the predictions of the gauge theory (QED) describing them, would not agree - according to an estimate of Brodsky and Sapirstein [3] unless the constituents have masses exceeding 10^5 GeV. The elementarity of quarks (no power-law falling off of their form factors) is pure hypothesis.

(2) For gauge theory purposes, both leptons and quarks must belong to the same fermionic multiplet.

(3) From (2), we - but not the majority of theorists - infer that <u>both</u> leptons as well as quarks must be integer-charged and <u>both</u> unconfined.

(4) A gauging of this fermionic multiplet will give rise to 1^- gauge mesons, among which are the photon, Z^0, $W^\pm$ as well as strongly interacting coloured octet vector gluons. These vector gluons - which carry integer charges - must also be unconfined.

To summarize, unconfined quarks and unconfined gluons will be the hallmark of our gauge unification of leptons and quarks.

These lectures will be concerned with the consequences of these ideas, some of which are the following:

(a) Since quarks and leptons belong to the same fermion multiplet, quarks can make transitions to leptons, $q \rightarrow \ell$, or to anti-leptons, $q \rightarrow \bar{\ell}$, with a violation of baryon-number and lepton-number, $\Delta B \neq 0$, $\Delta L \neq 0$. (We assign baryon-number +1 to quarks, lepton-number $L_e = +1$ to (ν_e, e^-) and $L_\mu = +1$ to (ν_μ, μ^-).

(b) Such transitions make quarks and protons unstable. The rate of such transitions is governed by the characteristic mass we have talked about earlier. In the basic model, the coupling parameter which determines quark decay rate into leptons comes out to be $\approx 10^{-8}\, m_N^2$, to compare to the Fermi constant $10^{-5}\, m_N^2$. As we shall see, quark decays into leptons provide a new - and potentially the most important - source of leptonic production in NN, νN and μN collisions at sufficiently high energies. The mechanism is a dissociation of nucleons into quarks and their subsequent decays into leptons. For $q \rightarrow \ell +$ mesons, $\Delta B = -\Delta L$, and nucleon dissociation will be a source of leptons ℓ rather than anti-leptons $\bar{\ell}$, while for $q \rightarrow \bar{\ell} +$ mesons, $\Delta B = \Delta L$, the opposite situation will prevail.

(c) Since quarks are unconfined and decay into leptons, within our model pair production of quarks is a potential source of multi-lepton events for e^-e^+ annihilation. As we shall see, in the context of the basic gauge model, the (μe) events [4] as well as the jet structure [5] observed at SPEAR receive a consistent explanation [6] in terms of real quark-anti-quark production (followed by their decays into leptons), provided there exists a coloured octet of vector mesons (e.g. the gluons) lighter than the quarks ($m_V < m_q \approx 1.8 \sim 1.9$ GeV).

(d) A characteristic consequence of our gauge model - tied to the unconfined quark hypothesis - is that the neutral as well as charged flavour gauge mesons (W's) must mix (through spontaneous symmetry breaking) with appropriate members of the octet of colour gluons. This induces colour excitation not only in eN and μN but also in νN interactions. We suggest that the excitation of the decaying colour gluons provides yet another prominent source of multi-leptons, on the one hand, and, on the other, the semi-asymptotic scaling violations [7] of the sort observed in νN as well as μN collisions; in particular the deviations discussed at this conference from the GIM parton model of quantities, $\langle Y \rangle_{\bar{\nu}}$, $\sigma_{\bar{\nu}}/\sigma_{\nu}$, and flat y-anomaly in $d^2\sigma_{\bar{\nu}}/dxdy$ can be attributed [7,8] to colour excitation within our model. For eN, μN and νN, we predict that if our ideas are correct, σ_L/σ_T is non-zero and scales as a function of x.

II. THE BASIC MODEL

Before any unification of quarks and leptons can be effected, one has to decide how many quarks and how many leptons. In 1972 one knew of four leptons ($\nu_e, e^- \rightarrow L_e = 1$; $\nu_\mu, \mu^- \rightarrow L_\mu = 1$) and suspected the existence of possibly twelve quarks (p, n, λ, c quarks in three colours - red, yellow and blue). It seemed a natural suggestion at that time to assign a fourth colour to leptons (lilac) and to postulate a basic sixteen-fold for all fermions belonging to the group $SU(4)|_{\text{flavour}} \times SU(4)'|_{\text{colour}}$

$$F = \begin{bmatrix} p_R & p_Y & p_B & \nu_e \\ n_R & n_Y & n_B & e^- \\ \lambda_R & \lambda_Y & \lambda_B & \mu^- \\ c_R & c_Y & c_B & \nu_\mu \end{bmatrix},$$

with the group theory forcing unique assignment of electric charge if we insist on either hadron $\leftrightarrow$ lepton or flavour $\leftrightarrow$ colour symmetry for electric charge:

$$Q = \begin{vmatrix} 0 & 1 & 1 & 0 \\ -1 & 0 & 0 & -1 \\ -1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \end{vmatrix}.$$

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

Heavy leptons and new flavours can arise within our unification hypothesis if we postulate a new heavy multiplet of similar basic structure - another sixteen fold. We in fact did consider such extended versions [1] of the basic model in 1973 - guided by various theoretical considerations. One of these considerations was the separation of electrons and muons from sharing the same multiplet [9], so that, for example, $K^0 \rightarrow e + \mu$ is strictly forbidden. In these lectures we shall stick to the basic model and try to make a case for understanding all presently known phenomena (including the so-called heavy lepton phenomena) within the context of this model. Our general philosophy is that the unconfined colour quantum numbers should be exploited as fully as possible before one adds on new (flavour) quantum numbers (besides GIM flavours) to resolve experimental problems of new $\bar{\nu}$N data. If the tests we propose in this context fail, we may be forced to extend the basic model as mentioned above. But what we wish to stress is that the idea of unification of leptons and hadrons lies deeper than the basic model. This particular model we consider is possibly an interim realization of the unification hypothesis. We shall, however, go on indicating which results are more general and which tied to this model.

The model

The model contains:

(1) Four leptons - which provide the FLAVOUR (up, down, strangeness and charm) quantum numbers.

(2) Twelve quarks - which carry four flavours × three colours.

(3) We suggest lepton-number $L = L^e + L^\mu$ is the fourth colour. Thus the number of colours equals the number of basic flavours.

(4) Define fermion-number F as

$$F = B(\text{the quark number}) + L^e + L^\mu .$$

This number equals 1 for quarks, (ν_e, e^-) and (ν_μ, μ^-) .

(5) We propose that for energies up to 10^5 GeV all processes conserve fermion-number,

$$\Delta F = 0 \implies \text{i.e. } \Delta B = -\Delta L .$$

There may be $\Delta F = 2$ transitions possible (by further extension of the model (i.e.(1) $q \to \bar{\ell}$ or (2) $q \to \ell_e$, $q \to \bar{\ell}_\mu$ or (3) $q \to \bar{\ell}_e$, $q \to \ell_\mu$ or (4) $q \to \bar{q}$ or (5) $\ell \to \bar{\ell}$ transitions) but we assume that these possess an effective transition probability smaller than $\Delta F = 0$ transitions. This insistence on the dominance of $\Delta F = 0$ transitions is the hall-mark of the basic model and its siblings - the so-called extended models. Unified models exhibiting $\Delta F = 2$ transitions have been constructed (for example by J. Strathdee and ourselves). They are best formulated in terms of Majorana fields. We shall not discuss them in any detail here, except to mention some of their expected consequences for quark decays.

(6) Either one of the pairs (ν_μ, μ^-) or (ν_e, e^-) is strange in this model, consistent with the empirical observation $|m_\Lambda - m_n| \approx |m_\mu - m_e|$.

(7) The flavour gauges are $SU_L(2) \times SU_R(2)$ with couplings g_L, g_R and six gauge fields $W_L^{\pm,0}$, $W_R^{\pm,0}$. The conventional $SU_L(2) \times U_R(1)$ is a sub-group of this anomaly-free gauge system $SU_L(2) \times SU_R(2)$ with [10]

$\frac{g_L^2}{4\pi} \simeq \frac{g_R^2}{4\pi} \sim \alpha$ and $\tan\theta_W \simeq \frac{g_R}{g_L}$. The mass parameter associated with the V + A currents m_{W_R} must empirically exceed 300 GeV, in order that V + A amplitudes in β and μ decays do not exceed the empirical limit of $\approx \frac{1}{10}$ (V-A) amplitudes.

(8) The colour gauge group is assumed to be $SU(4)|_{\text{colour}}$ with the coupling parameter $\frac{f^2}{4\pi} \sim (\frac{1}{2} - 1)$. This gives rise to fifteen gauge fields as follows:

(a) Exotics X^0, X^-, X'^- (and the anti-exotics) which couple with quarks and leptons (currents $\bar{q}\ell$). From the empirical branching rate of $K^0 \to e + \mu$, which these exotics contribute to, we assign $m_X \geq 10^5$ GeV to keep within the empirical limits. This is the major input in this model. Since the exotics couple with quarks and leptons: it is their mass m_X which eventually determines when quarks and leptons lose their distinction This is in analogy with the $W^\pm$ or Z^0 masses, which determine when neutrino interactions acquire electromagnetic strength. (In some of the alternative models [11] which are derived from the basic model or are extensions of it, one can arrange that $K \to e + \mu$ transition is forbidden. For such models m_X can be smaller than 10^5 GeV.)

(b) In addition to the exotics, there is the coloured gauge vector gluon octet $V(8)$ which couples quarks to each other strongly.

(c) One combination of fields among these eight gluon fields $U^0 = (\sqrt{3}\, V_3 + V_8)/2$ contributes to the photon field, which contains a flavour piece $(W_{3L} + W_{3R})$ plus the colour piece U^0. Symbolically $A/e \approx W/g + U/f$. Note that in its composition, the photon is more of a flavour field than a colour field $(g/f \sim \frac{1}{10})$.

(d) Finally, there is a vector singlet S^0 among the $SU(4)|_{\text{colour}}$ gauge particles, which couples with the current $(B - 3L)$ - and which would give a new weak neutral vector current, in addition to the conventional weak $SU(2) \times U(1)$, its strength depending upon the mass of S^0 $(m_{S^0} \gtrsim 1000$ GeV$)$.

(e) The mass matrix for quarks, exotics and gluons is provided by Higgs-Kibble mesons. Besides giving the masses of these particles (in terms of a total of five parameters - representing vacuum expectation values of Higgs-Kibble fields) the model also provides flavour-colour gauge meson mixing terms, in particular mixing of $V^\pm$ with $W^\pm$ (responsible for colour gluon decays) and $X^\pm$ mixing with $W^\pm$ (responsible for quark decays into leptons). The mixing parameters are also completely specified in terms of the five vacuum expectation values of the Higgs-Kibble fields.

As is well known, the Higgs-Kibble fields are at present the Achilles heel of gauge theories. There is no uniquely accepted canon as to which representations one should choose for them - except possibly the admonition of super-symmetry theory which would specify that they should belong to the same representation of the internal symmetry group as the basic fermionic multiplets in the theory. (It is worth remarking that such multiplets naturally permit both $\Delta F = 0$ as well as $\Delta F = 2$ transitions.) This lack of uniqueness as to the choice of Higgs-Kibble particles naturally affects the detailed predictions - and particularly the decay predictions of the model. To minimize model dependence in this respect, in the sequel we shall list only such predictions which depend on the bilinear mixing terms for gauge fields (W - V and W - X mixings). Such mixings arise as a consequence of the form of the mass matrices: <u>We shall not list those predictions which depend on exchanges or decays of Higgs-Kibble fields in the theory</u>.

(f) The (5-parameter) model discussed above assigns the following masses [12] to various particles:

m_X , $m_{S0} \geqslant 10^5$ GeV.

$m_{W_L} \geqslant 50$ GeV

$m_{W_R} \geqslant 10^4$ GeV

$m_V \approx$ either (1-2) GeV (Frascati, Orsay, Novosibirsk region Recall that one member of the octet $V_3 + V_8/\sqrt{3}$ mixes with the photon and should show itself as a peak in $e^+ + e^-$ experiments.)

$\approx$ or 4 GeV (SLAC, DESY region.)

Empirically there appear to be no narrow structures in $e^+ + e^-$ between 2-3 GeV which may be associated with colour. While the pattern of these gauge masses are fixed by the model - and can be changed only by changing the complexion of Higgs-Kibble mesons - the quark mass is still arbitrary up to a coupling parameter. To make things definite we choose two ranges for the free quark mass

i) light quark: $m_q \sim 2$-3 GeV, or

ii) heavy quark: 3 GeV $< m_q \leqslant 5$ GeV .

(g) Before closing this section, note that the quark dynamics - in the parton model context - appears to exhibit the phenomenon of PARTIAL CONFINEMENT - that is to say, the effective mass of quarks is smaller inside a nucleon (or a meson) than the free quark mass. The same may be true of gluon masses - and perhaps to a lesser extent for the exotic X masses. This effect was first discovered by Archimedes who felt lighter and freer in his bath-tub than outside it as a consequence of the beneficial effects of hydrostatic pressure - i.e. non-zero expectation value of the trace of the stress tensor $T_{\mu\mu}$, in modern language. The ARCHIMEDES EFFECT can be readily built into our model through such solutions for the field equations for which the expectation values (classical solutions) for the Higgs-Kibble fields are space-dependent in the manner made familiar by soliton physics.

III. CONSEQUENCES OF QUARK AND GLUON DECAYS; NEW SOURCES FOR MULTI-LEPTONS IN NN , νN , μN AND e^-e^+

1. In this section we consider the basic model in detail for its predictions of quark and vector gluon decays. We wish to use this information for considering multi-leptons of which there are three sources. These are:

a) Conventional charm mesons and baryons;

b) Coloured gluons and coloured baryons;

c) Unconventional baryon-number violating direct decays of integer-charge quarks into (leptons + mesons) and in particular (neutrinos + kaons), the quarks being produced as a consequence of nucleon dissociation or pair produced.

Since all quarks in our model decay into (leptons + mesons), the last mechanism must eventually become their most copious source. It is of particular interest to note that in the basic model the dissociation mechanism would give rise to the like-sign dilepton ($\mu^-\mu^-$) signal for νN , as observed experimentally [13].

The crucial points of the new mechanisms in the basic model with $\Delta B = -\Delta L$ are the following [6].

i) Yellow and blue quarks decay as a rule into neutrinos + mesons.

ii) It is only the charged red quarks (n_R^-, λ_R^-) which can at all decay into a charged lepton $(\ell^- + \bar{\nu} + \nu)$.

iii) In the basic model [1] there are no quark decays into (e^+, μ^+) + mesons nor any (non-electromagnetic) decays into two charged (plus one neutral) or three charged leptons + anti-leptons.

iv) One of the two lepton pairs (ν_e, e^-) or (ν_μ, μ^-) is strange. Strangeness is conserved in $|\Delta B| \neq 0$ quark decays, making (K + neutrino)-modes fairly copious.

v) For charged coloured gluon decays, the branching ratio of decays into leptons is rather high (typically 20 to 30% for either e or μ).

vi) For semi-leptonic decays of charged coloured gluons, K's and π's are not produced singly but in pairs.

2. We list in Tables II–IV the expected decay modes of charged coloured gluons $V^{\pm}$ and quarks in the basic model with $\Delta F = 0$. We assume, for the sake of definiteness, that the coloured gluons are the lightest coloured octet mesons. As stated before, since one member $(V_3 + (3)^{-1/2} V_8)$ of the coloured gluon octet[14] $(V^{\pm}_{RB}, V^{\pm}_{YB}, V^{0,\bar{0}}_{BY}, V_3, V_8)$ must be produced in $e^+ + e^-$ experiments, with a narrow width of a few MeV, we suggest that vector gluons $V^{\pm}_{RY}$, $V^{\pm}_{RB}$ may have masses in the following neighbourhood:

a) light gluon, in the Frascati region 1 - 2 GeV,

OR b) heavy gluon in the SLAC region ≈4.1 GeV.

Correspondingly, for quarks we shall consider light quarks $(m_q \approx 2 - 3 \text{ GeV})$ or heavy quarks $(3 \text{ GeV} < m_q \lesssim 5 \text{ GeV})$. These are physical masses outside of the nucleon environment [15]. The expected decay properties of the neutral gluons are listed in Table I.

A. Decays of charged colour gluons $(V^{\pm}_{RB}, V^{\pm}_{RY})$

These decay on account of their (spontaneously induced) mixing with the charged weak gauge bosons $W^{\pm}$, the mixing parameter being completely determined within the model. The inclusive hadronic versus electronic and muonic branching ratio is 3:1:1, for sufficiently massive gluons ($\gtrsim 3$ GeV), for which a light cone or parton model analysis is valid[6]. For lighter gluons (1 - 2 GeV), we expect hadronic versus electronic branching to be smaller than three - possibly of the order unity - on account of limited phase space, which restricts hadronic channels. For details see Table II. Note the crucial difference between colour and charm - the leptonic branching ratio of colour is larger (by a factor ≈2 to 5), and K's are produced in pairs (not singly) even in semi-leptonic decays.

B. Quark decays[6] in the basic model $(\Delta B = -\Delta L)$

As emphasised in Sec. I, red quark decays are crucially different from yellow and blue quark decays. There are four distinct cases for red quark decays depending on the relative masses of quarks versus gluons and of red quarks versus those of yellow and blue. The results are summarized in Tables III and IV.

In summary, only the charged red quarks can possibly be the source of charged leptons, so far as the basic model is concerned.

3. Conventional sources of multi-leptons in νN and $\bar{\nu}N$ scatterings:

First consider the conventional mechanism involving either single production of charm and colour or pair production of charm, colour or quarks:

(A) $\nu + N \to \mu^- + D + X$ (charm production ≈10%)

$D \to (\mu^+ \text{ or } e^+ + \cdots)$

(B) $\to \mu^- + V^+_{colour} + X$ (colour production ≈ 10 to 15%)

$V^+_{colour} \to (\mu^+ \nu_\mu)$ or $(e^+\nu_e)$

(C) $\to \mu^- + (D + \bar{D}) + X$

$D \to (\ell^+$ or hadrons) $\quad \bar{D} \to (\ell^-$ or hadrons)

(D) $\to \mu^- + (V^+ + V^-) + X$

$V^+ \to (\ell^+\nu_\ell$ or hadrons) $\quad V^- \to (\ell^-\bar{\nu}_\ell$ or hadrons)

(E) $\to \mu^- + (q^-_r + q^+_r) + X$.

$q^-_r \to (\nu+\ell^-+\bar{\nu}_\ell)$ or (ν+hadrons) $\quad q^+_r \to (\bar{\nu}+\ell^++\nu_\ell)$ or ($\bar{\nu}$+hadrons)

In the above $(D,\bar{D})$ and $V^{\pm}$ are only symbolic of the family of charm and colour particles with similar internal quantum numbers. Note that:

1) We expect single production of charm and colour (A and B) to exceed (perhaps by an order of magnitude) pair production (C,D,E) both on energetic grounds and from the fact that sea is relatively unimportant compared with valence.

2) Single production of charm and colour (A and B) should thus primarily be responsible for production of unlike-sign dileptons: $(\mu^-\mu^+$ and $\mu^- e^+)$ in νN and $(\mu^+\mu^-$ and $\mu^+e^-)$ in $\bar{\nu}N$. Following parton-model based calculations, we expect for both (A) and (B) $\langle E_{\mu^-}\rangle \gg \langle E_{\mu^+}\rangle$ for νN as well as large inelasticity; both these features are compatible with the data.[13] Contrast this with phenomenological lepto-hadron models, where this feature is not realized.[16]

3) Following familiar estimates, charm production ratio is expected to be of order 10% (corresponding to the "weight" of the sea), while the leptonic (e or μ) branching ratio of charm particles is expected $\approx(5 \sim 10)\%$. This yields

$$\left[\sigma(\mu^-\mu^+)_{charm}/\sigma(\mu^-)\right] \sim \left[\frac{1}{2} \text{ to } 1\right] \% \quad ,$$

which by itself is probably too low compared with the data.[17)]

4) Within the gauge theory approach,[1)] parton-model based estimates [18)] suggest colour production ratio at Fermilab energies $\approx(10\text{-}15)\%$ (with colour threshold ≈ 2 to 4 GeV); while the leptonic (e or μ) branching ratio of colour particles is ≈ 20 to 30% (see Table I). This yields

$$\left[\sigma(\mu^-\mu^+)_{colour}/\sigma(\mu^-)\right] \approx (2 \text{ to } 4)\% \quad .$$

This larger $(\mu^-\mu^+)$ rate appears to be more compatible with the present data than the charm estimate (by itself).

5) In νN, like-sign dileptons $(\mu^-\mu^-, \mu^-e^-)$ and trileptons $(\mu^-\mu^+\mu^-, \mu^-e^+\mu^-$ etc.) can arise from pair (or associated) production of charm, colour or quarks. Like dileptons arise from one member of the pair decaying leptonically and the other non-leptonically, while for trileptons both members of the pair decay leptonically.

For the pair (or associated) production mechanism mentioned above, charm (with its leptonic/non-leptonic branching ratio $\approx 1/10$ versus a ratio $\approx 1/3$ for colour) might possibly account better[19)] for $\sigma(\mu^-\mu^+\mu^-)/\sigma(\mu^-\mu^-)$, which experimentally appears to be $\lesssim 1/10$ (with essentially no trimuons seen). But any pair production hypothesis (from charm, colour or quarks) may come upon a dilemma from the ratio of $\sigma(\mu^+\mu^+)$ from $\bar{\nu}N$ versus $\sigma(\mu^-\mu^-)$ from νN. If pair production from νN and $\bar{\nu}N$ have comparable rates (see below), $(\mu^+\mu^+)_{\bar{\nu}}$ should be as likely as $(\mu^-\mu^-)_\nu$. It is too early to say yet if the preliminary experimental estimates of these processes are likely to pose a problem.

However, there is the totally different mechanism of dissociation of nucleons and quark decays, which has the feature that it does not give $(\mu^+\mu^+)_{\bar{\nu}}$ or trileptons in either νN or $\bar{\nu}N$. This may be operative in addition to any pair production mechanism.

4. <u>Deep inelastic nucleon dissociation into quarks and quark decays as a source of leptons</u>: Consider the following mechanism:

$$\begin{aligned}
\text{(F)} \quad \nu + \text{neutron} &\to \mu^- + \text{virtual } W + (n_y^0 + n_r^- + p_b^+) \\
&\to \mu^- + (p_y^+ + n_r^- + p_b^+) + X \\
&\to \mu^- + (\nu\pi^+) + (\mu^-\bar{\nu}\nu) + (\nu\pi^+) + X \quad .
\end{aligned}$$

Note that neutron's dissociation into valence quarks plus their $\Delta F = 0$ decays yields:

$$(\mu^-\mu^-)\text{'s in } \nu N \quad , \quad \text{and} \quad (\mu^+\mu^-)\text{'s in } \bar{\nu}N \quad ,$$

but <u>NO</u> $(\mu^+\mu^+)$'s in $\bar{\nu}N$, <u>NOR</u> any trimuons. This is because charged red quarks - the only source of charged leptons - cannot go into e^+, μ^+ but only into e^-, μ^-. Thus all $(\mu^+\mu^+)$'s in $\bar{\nu}N$ must be attributed to associated production of quarks charm (or colour). We can make the statement stronger: Since

$$\sigma^{\bar{\nu}}(\mu^+\mu^+)_{dissociation}/\sigma^{\nu}(\mu^-\mu^-)_{dissociation} = 0 \quad ,$$

while

$$\sigma^{\bar{\nu}}(\mu^+\mu^+)_{associated\ production}/\sigma^{\nu}(\mu^-\mu^-)_{associated\ production} \approx \frac{1 + 3\epsilon + \epsilon'}{3 + \epsilon + \epsilon'} \; ,$$

where ϵ denotes the sea (V + A) contribution relative to valence (V-A) contribution to associated production (which may be deduced from measurements of x distribution of the like-dileptons), while ϵ' denotes associated production due to colour current. Thus if the rate of $(\mu^-\mu^-)_{\nu N}$ is found to exceed that of $(\mu^+\mu^+)_{\bar{\nu}N}$ by a factor larger than 3 (for example even 4) it would be strongly suggestive of the dissociation mechanism being a significant source of the like-sign dileptons for νN. Another test is the x distribution of $\mu^-\mu^-$. Those like dileptons which originate from "valence" quarks (from dissociation) will probably exhibit a different x distribution from those arising from pair production, from the (valence + sea + gluons).

(G) From the universality of dissociation we expect

$$\left[\frac{\mu^- + N \to \mu^-\mu^- + X}{\mu^- + N \to \mu^- + X}\right]_{\text{dissoc.}} = \left[\frac{\nu + \text{neutron} \to \mu^-\mu^- + X}{\nu + \text{neutron} \to \mu^- + X}\right]_{\text{dissoc.}}$$

(H) In the deep inelastic p-p scattering process where one tags a final state proton, we may expect

$$\frac{p + p \to p + (\underset{\searrow \mu^-}{n_r^-} + p_y^+ + p_b^+) + X}{p + p \to p + \text{all}} \sim \frac{\nu + \text{neutron} \to [\mu^- + \mu^- + X]_{\text{dissoc.}}}{\nu + \text{neutron} \to \mu^- + X} \sim 10^{-3}$$

The last estimate (10^{-3}) is the present experimental number obtained from the rate of $(\mu^-\mu^-)$ production in neutrino scattering, assuming that it is all due to dissociation.

(J) In N-N collisions, one source of prompt e^- or μ^-'s is nucleon dissociation followed by red valence quark decay. Since (with $\Delta F = 0$, $\Delta B = -\Delta L$) this source will not yield e^+ or μ^+'s, we expect e^-/e^+, μ^-/μ^+ ratio >> 1 from this mechanism. In this context, it is worth stressing once again that in general there are four cases for quark to lepton or anti-lepton transitions. These are:

Basic model (1) $\Delta F = 0$, $\Delta B = -\Delta L$, expectation e^-/e^+, $\mu^-/\mu^+ \gg 1$ from dissociation.

Other possible models:

(2) $\Delta F = 2$, $\Delta B = +\Delta L$, expectation e^-/e^+, $\mu^-/\mu^+ \ll 1$ from dissociation.

(3) $\Delta B = -\Delta L_e = +\Delta L_\mu$, expectation e^-/e^+, $\mu^+/\mu^- \gg 1$ from dissociation.

(4) $\Delta B = +\Delta L_e = -\Delta L_\mu$, expectation e^-/e^+, $\mu^+/\mu^- \ll 1$ from dissociation.

The last two assumptions (3) and (4) go well with the Konopinski-Mahmoud model of leptons. The models (2), (3) and (4) are logically equally as possible as the basic model assumption ($\Delta F = 0$). However, in (gauge) model building we have found them somewhat difficult to implement. Although we have not considered the models based on these in any detail, the expectation may be that

if, for example, $\Delta B = +\Delta L_e = -\Delta L_\mu$, yellow and blue quarks decay into e^+ + mesons or (ν_e, ν_μ + mesons), while red quarks decay into μ^- + mesons or (ν_e, ν_μ + mesons). (Further, if e's are strange, non-strange, yellow and blue quarks may decay into e^+ + K's.)

(K) $\nu N \to \mu^- e^+ + K$'s;[17] In our model, a new mechanism for these events involves production of real $(c\bar{\lambda})$ quark pair from the $(\lambda\bar{\lambda})$ pair in the sea followed by quark decays to leptons:

$$\nu + (\lambda_y^0\bar{\lambda}_y^0)_{\text{sea}} \to \mu^- c_y^+\bar{\lambda}_y^0 \to \mu^- + (\underset{\llcorner \nu\bar{K}^0}{\lambda_y^0}\, e^+\nu) + (\bar{\nu}K^0)\ .$$

Using $\Gamma(c_y^+ \to \lambda_y^0 + e^+ + \nu_e)/\Gamma(c_y^+ \to \text{All}) \sim 10\%$ (see Table III) and a production ratio (due to sea) $\sim 10\%$, the expected rate of these events might be $\sim 1\%$.

Note that such a mechanism will enhance relative probabilities of single and multiple K associated events[20], which seems to be the trend of the data.[17]

(M) Multi-leptons in eN or μN due to colour production: For these processes, the colour current exchanged is neutral with no net colour quantum numbers. Thus there is the possibility of either producing a single coloured state with the quantum numbers of the neutral colour gluon $U^0 = (\sqrt{3}V_3 + V_8)/2$ or a pair of charged coloured particles, i.e.

$$\mu + N \to \mu + U^0 + X \qquad \text{or} \qquad \mu + N \to \mu + V^+ + V^- + X$$

$$U^0 \to \ell^-\ell^+ \text{ or } (\text{hadrons}+\gamma) \text{ or hadrons}; \qquad V^+ \to \mu + \nu, \qquad V^- \to e^-\bar{\nu}$$

Leptonic branching ratio for the neutral colour gluon is rather small [21] ($\sim 10^{-3}$). For this reason, even though we may expect $\sigma(V^+V^-) \sim (\frac{1}{10} \sim \frac{1}{30})\sigma(U^0)$, pair production of colour is expected to be the more copious source of multi-leptons. Taking inclusive colour production ratio [18] at Fermilab energies to be ≈ 10 to 15%, we estimate $\mu^- : \mu^-\mu^\mp : \mu^-\mu^+\mu^- : \mu^-\mu^+e^- \approx 1 : 10^{-3} : 1/3000 : 1/3000$; this is compatible with the recent Fermilab data.[22]

To conclude, two new mechanisms (with their characteristic signatures) have been proposed in this note, for multi-lepton production in νN, μN and NN which may possibly be operative at present experimental energies, depending on the masses of gluons and quarks and their production rates. These are coloured gluon and quark decays arising through quark pair production and nucleon dissociation into integer-charge unconfined quarks, which in their turn decay into leptons if $\Delta B = -\Delta L$ and anti-leptons if $\Delta B = +\Delta L$.

5. Integer-charge quarks as source of SLAC μe events: One of the hallmarks of the hypothesis of unconfined quarks is that $q\bar{q}$ as well as charged colour gluon parton pairs produced by e^-e^+ annihilation must materialize (at least part of the time) as real particles above threshold. These, followed by their decays into leptons, become then a potential source of multi-leptons in e^-e^+ annihilation. In particular, following Tables II, III and IV, the charged red quark pairs and charged colour gluons will give rise[6] to signature μe events as observed at SLAC; subject, however, to two conditions: i) at least the (p,n) quarks are as light as about 1.7 to 2 GeV, and ii) so far as the basic model is concerned there exist coloured octet vector mesons (e.g. the gluons) lighter than the quarks [23].

To deduce the strength of the (μe) signal expected from quark and gluon pair production, we note that within the colour gauge theory [1] framework, the colour octet part of quark charges do not asymptotically contribute to R (this is discussed in Sec.IV). Taking this into account, the contributions to the R parameter from quarks and colour-gluons (treated as partons) are given by:

$$R(p_r^0\bar{p}_r^0) = R(p_y^+p_y^-) = R(p_b^+p_b^-) = 4/9$$

$$R(n_r^-n_r^+) = R(n_y^0\bar{n}_y^0) = R(n_b^0\bar{n}_b^0) = 1/9$$

$$R(\lambda_r^-\lambda_r^+) = R(\lambda_y^0\bar{\lambda}_y^0) = R(\lambda_b^0\bar{\lambda}_b^0) = 1/9$$

$$R(c_r^0\bar{c}_r^0) = R(c_y^+c_y^-) = R(c_b^+c_b^-) = 4/9$$

$$R(V_\rho^+V_\rho^-) = R(V_{K*}^+V_{K*}^-) = 1/16 .$$

Note the intriguing feature that asymptotically the neutral pair $(p_r^0\bar{p}_r^0)$ contributes the same amount to R as the charged pairs $(p_{y,b}^+, p_{y,b}^-)$. The contributions to R listed above (presumably) represent the sum of real $(q\bar{q}, V\bar{V})$ production and the parton pair recombination into hadrons.

Turning now to the origin of the SPEAR (μe) events, pair production of the yellow and blue quarks (even though present) cannot be responsible for these events, since these quarks decay predominantly semileptonically into $(\nu_{e,\mu}$ + mesons) (see Table III). On the other hand, if quarks are heavier than the colour-gluons and $(m_r - m_{y,b}) < m_\pi$ (case 3), pair production of charged red quarks $(n_r^-\ n_r^+)$ and $(\lambda_r^-\ \lambda_r^+)$, followed by their sequential decays as shown below can give rise to anomalous (μe) pair as seen at SPEAR so far as the basic model is concerned:

$$e^- + e^+ \to n_{red}^- + n_{red}^+$$

$$n_{red}^- \to V_\rho^- + \nu_e, \quad V_\rho^- \to e^- + \bar{\nu}_e; \qquad n_{red}^+ \to V_\rho^+ + \bar{\nu}_e, \quad V_\rho^+ \to \mu^+ + \nu_\mu .$$

The (μe) pairs thus arising would appear within the present statistics like three-body leptonic decay of the parent quarks.[24]

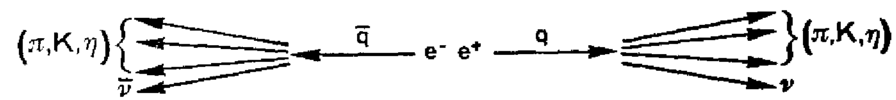
Now define $\rho(s) \equiv |f_{qq\gamma}(s)|^2$, where $f_{qq\gamma}(s)$ is the on mass-shell-quark electromagnetic form factor. It follows that $\sigma(e^-e^+ \to q_i\bar{q}_i)/\sigma(e^-e^+ \to \mu^-\mu^+) = R(q_i\bar{q}_i)\rho(s)$, where $R(q_i\bar{q}_i)$ for any given quark parton pair is given above. (Note that strictly within the parton model hypothesis we may interprete $\rho(s)$ as the fraction of all $q_i\bar{q}_i$-parton-pairs created, which "survive" as real particles in the final state. We refer to $\rho(s)$ as the "quark-survival factor"). Noting that asymptotically $R(n_r^- n_r^+) + R(\lambda_r^-\lambda_r^+) = 2/9$ and that the branching ratio of the $(\mu\nu)$ as well as $(e\nu)$-decay modes of $V_\rho^\pm$ is $\approx$ (25 to 35)% (as discussed before), the net contribution to R of the $(\mu^\pm e^\mp)$ signals arising from real quark-production and decays is given by $R_{q\bar{q}}(\mu^+e^-) = R_{q\bar{q}}(\mu^-e^+) = (2/9)(1/4 \text{ to } 1/3)^2\rho(s) = \rho(s)(1.6 \text{ to } 2.5)\%$.

Direct production of charged color-gluon pairs followed by their two-body leptonic decays[25] will also contribute to the signature (μe)-events. Noting that $R(V_\rho^+V_\rho^-) + R(V_{K^*}^+V_{K^*}^-) = 1/8$, the net contribution to $R(\mu^\pm e^\mp)$ from color-gluon pair-production is given by $R_{V\bar{V}}(\mu^+e^-) = R_{V\bar{V}}(\mu^-e^+) = (1/8)(1/5 \text{ to } 1/3)^2\rho'(s) = \rho'(s)\ (0.8 \text{ to } 1.4)\%$, where $\rho'(s)$ is the "color-gluon-survival factor."

The observed SPEAR (μe)-signal corresponds to a true-signal of $R(\mu^+e^-) = R(\mu^-e^+) \approx (1 \text{ to } 3)\%$ (allowing for momentum and solid angle cuts). Comparing with the estimate given above, this can be attributed to quark-decays only provided the square of the quark-electromagnetic form-factor is of order unity ($\rho(s) \equiv |f_{qq\gamma}(s)|^2 \sim 1/2$ to 1). Not knowing theoretically the precise nature of the quark-electromagnetic factor, we will proceed in these lectures with the assumption that it is hard (i.e. $f_{qq\gamma}(s) \sim (1/\sqrt{2})$ to 1 and slowly varying at SPEAR energies) unlike the form factors of composite systems such as the nucleon or the

pion. There then exist a host of strong experimental predictions of our hypothesis that the SPEAR dilepton events arise from quark decays <u>and</u> of the assumption that quark form factors are hard, as mentioned above. These we list below:

(i) <u>Jet-like distribution of hadrons</u>: First, within the quark hypothesis for the μe events, a large fraction $\rho(s)$ ($\approx \frac{1}{2}$ to 1) of the total hadronic annihilation events must contain a real quark and an antiquark emerging with equal and opposite momenta. (The different kinds of quark pairs would, of course, be produced in proportion to their contribution to the R parameter (see list above). Since most of the quarks (apart from n_r^- and λ_r^-) decay relatively rapidly predominantly into (<u>neutrino</u> + known mesons), <u>these $q\bar{q}$ pairs would give rise to the final state hadrons (mesons) emerging in the form of two jets opposite to each other with a distribution characteristic of spin-$\frac{1}{2}$ parentage</u>. Such



Hadronic Jets in e^-e^+ Annihilation

<u>Fig.1</u>

jet structure is indeed observed experimentally[5] at SPEAR. Since quarks carry charges, 0 ± 1; within our hypothesis we expect some of the jets to carry a net charge ± 1 and some to be neutral. The ratio of charged to neutral jets should reach a value $(18/9)/(12/9) = 3/2$ above charm quark threshold but below threshold for new flavours (if there exist any).

We are not aware of <u>any</u> convincing explanation of the jet structure for e^-e^+ annihilation in the confined quark model. It seems to us that the standard lore that "spin $\frac{1}{2}$ parton antiparton creation explains the observed jet structure" is indeed true, provided the parton quantum numbers appear in the jets (as we suggest here).

(ii) <u>Energy crisis</u>: Furthermore, these events must be associated with missing neutral energy and momentum carried away by the neutrinos, which may explain the so-called "energy crisis" and the depletion of charged energy observed in e^-e^+ annihilation.

(iii) <u>Depletion of charmed particle production</u>: If the charmed particles D and F are relatively heavy compared with the charmed quarks; the charmed quarks rather than decaying into $(\nu + D)$ or $(\nu + F)$ would decay preferentially into (uncharmed quark + pions) (see Tables III and IV). In this case, production of <u>real</u> charmed quark pairs above threshold (this may lie between 5 to 6 GeV) will lead to an increase in $R = 4/3\ \rho(s)$; but <u>this</u> increase will be reflected more in the production of pions and kaons rather than charmed mesons leading to a depletion of charm signature compared with the expected strength for $\Delta R = 4/3$.

(iv) V $\mp$ A-Coupling: Given that the W_L gauge mesons couple to V-A-currents, it is easy to see that the amplitude for the transition $n_r^- \to V_\rho^- + (n_y^\circ)_{virtual} \to V_\rho^- + \nu_e$ must be proportional to $\bar{\nu}_e(1+\gamma_5)[F_1\gamma_\mu + F_2\sigma_{\mu\nu}q_\nu]n_r^- V_{\rho\mu}^+$ which is of the V + A-form for $F_2 = 0$.

(v) Semileptonic Signals: In addition to pure leptonic signals (as shown) there must exist semileptonic signals such as $e^-e^+ \to \mu^\pm e^\mp + \pi^+ + \pi^-$ + missing momentum, which arise from semileptonic decay modes of either the color gluons (produced via quark decay) or directly of the charged red quarks. We estimate the strength of such semileptonic signals to be $\approx$ 2 to 5% of the pure leptonic signals. Note by contrast, semileptonic signals as above can not arise via pair-production and decays of heavy leptons. Pair-production of conventional charmed particles ($D\bar{D}$, $F\bar{F}$), if it occurs, can give rise to semileptonic signals, but these signals should preferentially involve K particles. Thus a search for the semileptonic (μe) signals is of crucial importance.

(vi) Neutral quark-pair production: One of the most interesting distinctions (within the gauge approach between quark and heavy lepton-hypotheses for the SPEAR (μe)-events is that the neutral quark-pairs $p_r^\circ\bar{p}_r^\circ$ and $C_r^\circ\bar{C}_r^\circ$ would each be produced asymptotically with a cross section given by $R = (4/9)\,\rho(s)$ (See list above), which is four times that of the charged pair $n_r^- n_r^+$; neutral heavy leptons on the other hand can not be produced by e^-e^+-annihilation. Assuming that p_r° decays predominantly radiatively to $(n_{y,b}^\circ + \gamma)$ (which holds if $m(p_r^\circ) - m(n_{y,b}) \geq 10$ MeV), the production of p_r° may be searched for by looking for monoenergetic low-energy ($\approx$ 10 to 100 MeV) γ-rays near theshold for the production of $p_r^0\bar{p}_r^0$ pair, which should nearly coincide with the threshold for quark originated (μe) events. Note we expect $m(p_r) \approx m(n_r)$.

(vii) Inclusive muon-production experiment [26] ($e^-e^+ \to \mu + X$): The Maryland-Pavia-Princeton collaboration data of the inclusive muon production was used by Snow [27] to set the following limit for the decay modes of the source "U" of anomalous muons:

$$\frac{\text{"U"} \to n_{ch} \geqslant 3}{\text{"U"} \to n_{ch} = 1} < 0.33 \;.$$

Snow used this limit to eliminate charm particles as the major source of the μe events. For quarks and gluons, since charged gluons decay into hadrons only nearly 30% of the time and since not all hadronic modes contain $N_{ch} \geqslant 3$, we estimate the above ratio to be $\leqslant 0.2$, fully consistent with the data.

To conclude, the quark hypothesis for the SPEAR (μe) events leads to several intriguing consequences; in particular it explains the jet-like distribution of hadrons and possibly also the depletion of charged energy in e^-e^+ annihilation. We emphasise once again that the SPEAR (μe) events may arise from quark decays so far as the basic gauge model is concerned, provided there exist the colour gluons (or similar coloured vector mesons) at 1 to 2 GeV.

Pati, Sucher and Woo [28] have studied the consistency of such light mass gluons with the presently available data. They conclude that while a gluon mass < 1 GeV is unlikely (due to constraints from $(g-2)_\mu$, photoproduction experiments and gluon life-time considerations), a gluon mass in the range 1.1-1.8 GeV is compatible with the present data. For the neutral gluon, they estimate (see Table I): $1\ \text{MeV} \leqslant \Gamma(\tilde{U})_{total} \lesssim 10$ MeV, $\Gamma(\tilde{U} \to e^+e^-) \approx 2$ to 10 keV. Such a neutral gluon should be visible prominently in e^-e^+ annihilation at Frascati, Novosibirsk and Orsay. We strongly urge such a search. A search for this gluon $\tilde{U}$ in photoproduction is also in order. A signal

$$\frac{\sigma(\gamma + p \to \tilde{U} + X \to e^-e^+ + X)}{\sigma(\gamma + p \to \rho^0 + X \to e^-e^+ + X)} \sim 10^{-2}\ ((\tfrac{1}{5} \text{ to } 5)$$

is expected [28]. Finally, to distinguish between quark versus heavy lepton hypotheses for the (μe) events, we urge searches for (i) anomalous semi-leptonic (μe) signals in e^-e^+ annihilation and (ii) monoenergetic low-energy γ rays near threshold for the production of (μe) events.

IV. THE UNCONFINED COLOUR GLUONS; LEPTO-PRODUCTION OF COLOUR

The first major plank of our unified theory is integer-charge quarks decaying into leptons. The second is integer-charged 1^- gauge colour gluons which acquire mass through spontaneous symmetry breaking. The operative word here is gauge; by which we imply "renormalizable gauge theories" in which the local symmetry is broken and thereby the corresponding gauge mesons acquire mass (if at all) only through spontaneous symmetry breaking. We show that there are crucial differences between the dynamics of gauge versus non-gauge (Han-Nambu [29]) theory of integer-charge quarks and colour 1^- particles. It is the gauge character of colour gluons which saves the integer-charge quark theory from some of its alleged shortcomings relative to the experimental data as well as for some of its successes, which we wish to point out. In particular for eN, μN and νN, these gauge aspects lead us to predict:

(1)

$(\sigma_L/\sigma_T) \neq 0$ and asymptotically it must scale — For the unified gauge theory [1] of integer-charge quarks and (massive) charged spin-1 colour gluons (I).

By contrast

$(\sigma_L/\sigma_T) \propto (q^4/m^4)$ — For non-gauge (Han-Nambu) theory of integer-charge quarks with charged spin-1 colour gluons (II)

$(\sigma_L/\sigma_T) \longrightarrow 0$ — For the unified gauge theory of fractionally charged quarks and (massless) neutral spin-1 colour gluons (colour is confined, in this case, by assumption) (III).

Note that the prediction of the non-gauge (Han-Nambu) theory of integer-charge quarks (Case II) is clearly incompatible with the data unless one assumes that colour threshold is sufficiently above 5 GeV. The prediction of confined colour (Case III) that (σ_L/σ_T) should be vanishingly small in the deep inelastic region also appears difficult to reconcile with the present data (especially if one follows the recent theoretical analysis of Politzer [30]). For the gauge theory of integer-charge quarks (unconfined colour) - Case I - on the other hand, we derive [18] that (σ_L/σ_T) should be non-vanishing though small compared with unity (lying between 0.1 and 0.3) in the bulk of the presently explored regions of q^2 and ω, consistent with the present data. [31]

(2) For the sum rule [32] on ($eN/\nu N$) ratio (designed originally to test quark changes) we predict [7]:

$$r \equiv \frac{4G_F^2 M_N E_\nu}{2\pi(\sigma_\nu + \sigma_{\bar\nu})} \int F_2^{\gamma N} = 0.28 \pm 0.03$$ — Gauge theory of integer-charge quarks (I).

By contrast:

$r = 0.5$ — Non-gauge (Han-Nambu) theory of integer-charge quarks (II)

$r = 0.28$ — Gauge theory of fractionally charged quarks (III)

$r_{expt.} = 0.27 \pm 0.05 (E_\nu > 30$ Gev) (Ref. 33) .

We see that the experimental value of r disfavours the non-gauge theory of integer-charge quarks (Case II) as does the behaviour of σ_L/σ_T (assuming that colour threshold is below 5 GeV), it however agrees well with the predictions of both Case I (gauge theory of integer-charge quarks) and Case III (gauge theory of fractionally charged quarks). This agreement of theory versus experiment for the ratio r for these two cases should thus be regarded, in our opinion, as one of the brilliant successes of parton-model ideas within the gauge context (asymptotic freedom); but within this context, contrary to the widely spread impression, this ratio is not sensitive to help distinguish between integer versus fractionally charged quarks (Case I and Case III). It helps eliminate (subject to parton-model considerations) a non-gauge approach to integer-charge quarks (Case II).

(3) For colour versus flavour excitations in deep inelastic eN and μN scatterings above threshold for colour production (assumed $\lesssim 5$ GeV), we predict:

(i) $\dfrac{d\sigma^{colour}}{d\sigma^{flavour}} \lesssim 10$ to 20% for a bulk of the presently explored regions of q^2 and ω

(ii) Predict non-asymptotic scaling violations (~ 10 to 20%) due to colour production (above and beyond log corrections), which must decrease like (m_U^4/q^4) and (m_U^2/q^2), where m_U = mass of gluon.

— For the gauge theory of integer-charge quarks (I)

By contrast for Case II, we expect [34]:

$\frac{d\sigma^{colour}}{d\sigma^{flavour}} \approx 100\%$ (from quark charges alone); gluon charges would lead to additional contributions growing like q^4/m^4) — For non-gauge (Han-Nambu) theory of integer-charge quarks (II),

while for Case III,

$\frac{d\sigma^{colour}}{d\sigma^{flavour}} = 0$; all scaling violations must be attributed solely to log corrections [35] (from asymptotic freedom) and to excitation of new flavours, if there exists any, in the transition regions. — For the gauge theory of fractionally charged quarks (III).

Experimentally, no large rise (~ 100%) in structure functions is observed even at Fermilab energies, which once again disfavours the non-gauge theory of integer-charge quarks (Case II). Combining these crucial distinctions (1), (2) and (3) between the non-gauge versus the gauge approach to integer-charge quarks, and the corresponding comparisons with the data, we thus deduce that if quarks carry integer-charges, the underlying theory must have a gauge origin. Furthermore, since such a gauge structure requires a minimum of four flavours, the number of quarks must be at least 12 (rather than 9) implying that the theory possess charm in addition to colour.

To choose unambiguously between the gauge theories of integer-charge and fractionally charged quarks (I and III), one crucial measurement is the determination of (σ_L/σ_T) at high $|q^2|$ and $M_N \nu$ (in particular with high ω).

(4) For νN and $\bar{\nu}N$, the definite $V^{\pm} - W^{\pm}$ mixing within the gauge theory of integer-charge quarks [1] implies that neutrinos and anti-neutrinos can also excite colour [36] in this theory just like electrons and muons. In particular, we show that the non-leading (kinematic) terms [7),8)] in gauge gluon theory gives a reasonable explanation of deviations of $(\sigma_{\bar{\nu}}/\sigma_{\nu})$, $\langle y \rangle_{\bar{\nu}}$ and $d^2\sigma_{\bar{\nu}}/dx\,dy$ from GIM predictions in a parton-model context without need for introducing [37] any new flavours associated with b quarks and V+A currents. Thus we suggest together with the authors of Ref. 8, that if new quantum numbers are needed in addition to GIM flavours, these are the familiar colour quantum numbers, unexploited in the colour confinement theory (Case III).

Before we discuss the empirical manifestations of gauge coloured mesons, we state and prove a theorem (independently proved [7),38)] by Rajasekharan and Roy and by ourselves last Summer) which highlights the difference between the dynamics of gauge [1] versus non-gauge coloured 1^- particles and explains the results states in (1)-(4) above.

Theorem

For all spontaneously broken gauge theories [39], which (i) gauge flavour and colour independently (weak interactions being associated with flavour gauging and strong with colour gauging), (ii) which lead to integer-charges for quarks, and (iii) in which leptons are introduced as SU(3)' colour singlets; electro- or muon production of colour ($e + N \to e + X_{col}$) proceeds through exchange of two gauge bosons: the "coloured" photon A_μ as well as its orthogonal colour gauge partner $\tilde{U}_\mu$; the two contributions tend to cancel each other. Because of this cancellation effect, there is a damping factor $\Delta^2 = [m_U^2/(|q^2| + m_U^2)]^2$ for electro- or muon production of colour. No such factor is present for lepto-production of flavour, i.e. colour singlet states. In these theories neutrinos can also produce colour (i.e. $\nu_\mu + N \to \mu + X_{col}$) subject, however, to the same damping factor Δ^2. The net effect is that above colour threshold ($W^2 \equiv M_N^2 + 2M_N\nu - |q^2| > M_{col}^2$), lepto-production structure functions (receiving contributions from both flavour and colour currents) take the form:

$$F_i(q^2,\nu) = F_i^{flav}(q^2,\nu) + \left(\frac{m_U^2}{|q^2| + M_U^2}\right)^2 F_i^{col}(q^2,\nu) \quad .$$

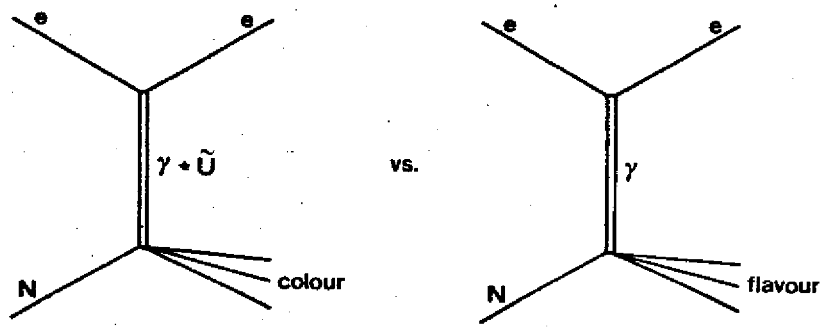
where F_i^{flav} and F_i^{col} are defined in the usual manner by the Fourier transforms of the respective current correlation matrix elements. It is on account of this damping factor $\Delta^2 = [m_U^2/(|q^2| + m_U^2)]^2$ that (i) colour production, though non-vanishing, is suppressed to the 10-20% level (relative to colour singlet flavour production) and (ii) $(\sigma_L/\sigma_T) \neq 0$ and it scales [7),38)] as a function of x. [For the non-gauge theory [29] of integer-charge quarks, electro-production of colour would take place only through the photon intermediary and thus no such cancellation factor Δ^2 would arise in this case.]

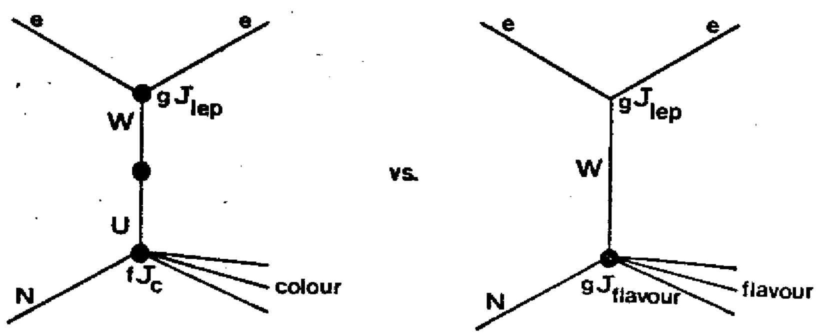
Proof

The origin of the colour damping factor Δ^2 within the gauge approach is very easy to comprehend. It comes about basically because leptons are introduced into the theory (strictly) as SU(3)' colour singlets.

Write the gauge-Lagrangian symbolically in the form: $L_{int} = g\,W\,J_W + f\,V(\underset{\sim}{8})\,J_{colour}$. Here W stands for the weak and $V(\underset{\sim}{8})$ for the strong colour gauges, while the photon field is a mixture: symbolically $\frac{1}{e}A = \frac{1}{g}W + \frac{1}{f}U$ $\left(\frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{f^2};\ \frac{g}{f} \approx \frac{1}{10}\right)$; $J_W = J_{flavour} + J_{leptons}$ and $U^0 = \frac{1}{2}(\sqrt{3}\,V_3 + V_8)$.

[We have, for convenience of writing (but with no loss of generality) lumped all SU(3)' colour singlet gauge fields (even if it arises due to strong gauging of a colour symmetry bigger than SU(3)' (for example SU(4)', see Ref.1) into W; correspondingly J_{flavour} contains flavour singlet as well as flavour octet but colour singlet terms.] Notice now that before spontaneous symmetry breaking (when all fields are massless) leptons interact with the colour singlet flavour current (J_{flavour}) through the intermediary of W_μ's – but there is no interaction between J_{leptons} and J_{colour}. Because of spontaneous symmetry breaking flavour and colour gauge mesons mix. This generates (through diagonalization of fields) the massless coloured photon A_μ (with integer-charges for quarks); but inevitably also the orthogonal colour gauge partner $\tilde{U}_\mu$ (with mass m_U), both of which contribute to lepton colour interaction. The photon and $\tilde{U}_\mu$ contributions would cancel each other except for the difference between their propagators. Due to this cancellation effect colour production matrix element is proportional to $\left(\frac{1}{q^2} - \frac{1}{q^2 - m_U^2}\right) = \frac{1}{q^2}\left(\frac{-m_U^2}{q^2 - m_U^2}\right)$ to be compared with colour singlet flavour production matrix element $\propto 1/q^2$. Diagrammatically, we want to compare





i.e. the propagators fg WU vs. g^2 WW ; assuming that the dynamical factor $\langle N|J'_{\text{colour}}|\text{colour}\rangle$ and $\langle N|J_{\text{flavour}}|\text{flavour}\rangle$ would lead to similar behaviour for the inclusive cross-sections (sufficiently above threshold).

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:

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

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

$$\frac{e + N \to \text{colour}}{e + N \to \text{flavour}} = \frac{f}{g}\,\frac{\langle WU\rangle}{\langle WW\rangle}\,\frac{(N|J_{\text{colour}}|\text{colour})}{(N|J_{\text{flavour}}|\text{flavour})}$$

$$= \left(\frac{1}{q^2} - \frac{1}{q^2 - m_U^2}\right) \Big/ \left[\frac{1}{q^2} + O\left(\frac{g^2}{f^2}\right)\right] \times \text{dynamical factor}$$

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

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

(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 for the region, where $|q^2|$ and $M_N\nu$ are small compared with m_U^2. As we all know, the structure functions $F_i(q^2,\nu)$'s are expected to scale (following parton model or asymptotic freedom considerations) for $|q^2|$ and $M_N\nu$ sufficiently large compared with characteristic $(\text{mass})^2$.

However this scaling so far as F_i^{flavour} are concerned does not set in fully until $|q^2|$ empirically reaches the value $\approx 2m_\rho^2$ (as may be deduced from the lower energy SLAC data [33], see Fig. below). We shall assume that a similar (precociously scaling) dynamical effect is operative for F_i^{colour} as well, except that $|q^2|$ (and $M_N\nu$) must reach characteristic colour (mass)^2 $\approx 2m_{\text{col}}^2$ (rather than characteristic flavour (mass)$^2 \approx 2m_\rho^2$) before full scaling is operative. This dynamical effect provides another suppression source for colour (and flavour) production in the low $|q^2|$ low ν region (i.e. for $|q^2|$ and/or $M_N\nu \lesssim 2m_\rho^2$ for flavour and $|q^2|$ and/or $M_N\nu \lesssim 2m_{\text{col}}^2$ for colour). Such a suppression may be represented by scale threshold factors $\rho_{\text{flavour}}(q^2,\nu)$ and $\rho_{\text{colour}}(q^2,\nu)$, which (by definition) acquire their full scaling weight unity for appropriately large $|q^2|$ and $M_N\nu$. Taking this into account, finally we expect (above colour threshold)

$$\frac{d\sigma_{\text{colour}}}{d\sigma_{\text{flavour}}} \approx \left|\frac{m_U^2}{|q^2| + m_U^2}\right|^2 \frac{\rho_{\text{colour}}(q^2,\nu)}{\rho_{\text{flavour}}(q^2,\nu)} ,$$

where

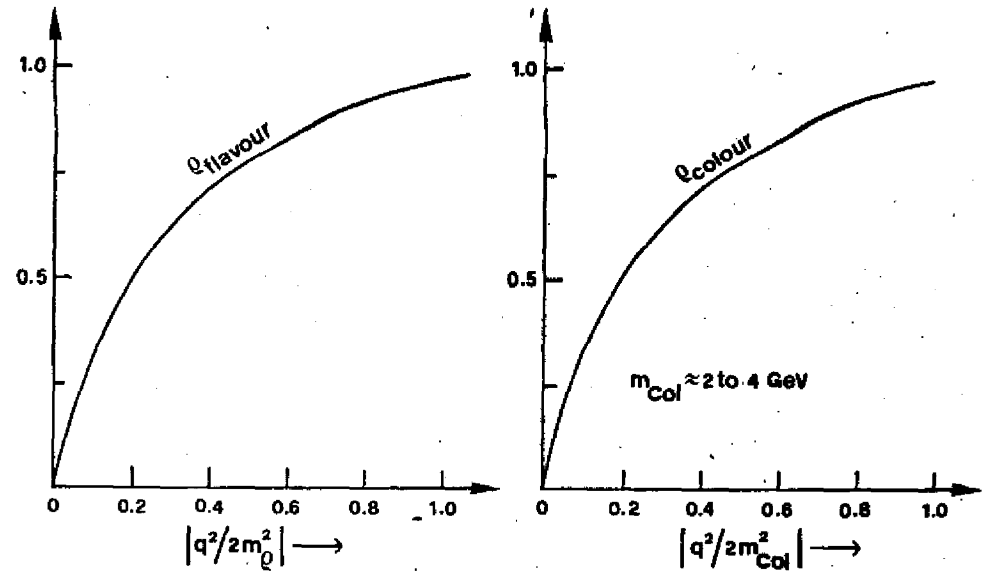
$$0 \leq \rho_{\text{colour}}(q^2,\nu) < 1 \qquad (0 < |q^2| < 2m_{\text{col}}^2)$$

$$\rho_{\text{colour}}(q^2,\nu) = 1 \qquad (|q^2| \text{ and } M_N\nu \gtrsim 2m_{\text{col}}^2)$$

Similarly define $\rho_{\text{flavour}}(q^2,\nu)$. We assume that the effective colour mass m_{col} above which ρ_{col} should acquire its scaling weight units is of order 2 to 4 GeV, corresponding to a likely place where the threshold for colour continuum may begin [40].

Using the empirically determined shape of the scale threshold factor $\rho_{\text{flavour}}(q^2,\nu)$ as a function of $|q^2|$ with $M_N\nu$ being $\gtrsim 2m^2$ (which may be deduced from the lower energy SLAC data [33]), we exhibit (in Fig.2b) $\rho_{\text{colour}}(q^2,\nu)$ for fixed large ν). We have assumed (in accordance with the discussions above) that $\rho_{\text{colour}}(\eta_{\text{col}},\nu) = \rho_{\text{flavour}}(\eta_{\text{flav}},\nu)$, where $\eta_{\text{col}} \equiv |q^2|/2m_{\text{colour}}^2$, while $\eta_{\text{flavour}} \equiv |q^2|/2m_\rho^2$.

Substituting numbers (with $m_U = 1.2$ to 2 GeV or $m_U = 4$ GeV, and $m_{\text{col}} = 2$ to 4 GeV) into the ratio $(d\sigma_{\text{colour}}/d\sigma_{\text{flavour}})$ for a feel only (we present detailed estimates later), it is easy to verify that the suppression factor for colour (relative to flavour) is $\approx \frac{1}{8} - \frac{1}{10}$ for both SLAC and FNAL.



(a) Scale threshold factors (b)

Fig.2

It is important to note that the structure function F_2 derived from deep inelastic muon scattering at the higher energy Fermilab data (where one might qualitatively expect colour to be excited) does not exhibit [41] even approximate scaling until $|q^2| \gtrsim 4$ to $10(\text{GeV})^2$ in contrast to the lower energy SLAC data. It is provocative that such a picture (with 10 to 20% but not 100% rise in the structure functions) is indeed what one might have expected from colour excitation within the gauge context (see ρ_{colour}, Fig.2b and multiply by the gauge damping factor Δ^2).

Colour contribution to eN and νN structure functions

The gauge character of $V(\underset{\sim}{8})$ gluons has an important bearing on the gluon contribution to the structure functions. Bell, Llewellyn-Smith and others have shown that in a renormalizable gauge theory the high energy, high momentum transfer behaviour of gauge spin-one gluons is similar to that of 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-renormalizable massive spin-one particles. For example, if $V(\underset{\sim}{8})$ 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 $\Delta^2 = \left|\frac{m_U^2}{|q^2| + m_U^2}\right|^2$ helps in restoring scaling behaviour to both F_1 and F_2 when $|q^2| \to \infty$. More specifically (including the gauge factor Δ^2 as well as the scale threshed factor $\rho_{col}(q^2,\nu)$ for colour production) we obtain:

$$F_1 = F_1\ (\text{GIM flavour}) + a(1+\xi)^{-2}\left[\sum_{p,n,\lambda,c}\left\{q(x) + \bar{q}(x)\right\} + 16\left(1 + \frac{\xi}{4}\right)v(x)\right]\rho_{col}(q^2,\nu)$$

$$F_2 = F_2\ (\text{GIM flavour}) + 2a(1+\xi)^{-2}\left[x\sum_{p,n,\lambda,c}\left\{q(x) + \bar{q}(x)\right\} + 2x\, v(x)(3 + \xi + \xi^2/4)\right]\rho_{col}(q^2,\nu)$$

$$F_3 = b\, F_3\ (\text{GIM flavour}),$$

where the second terms in F_1 and F_2 represent contributions from colour production. There is no contribution from colour to F_3, because colour gauge mesons possess vector couplings only [42] (in the basic model). An energy threshold factor $\Theta(W - W_{th}^{col})$ is not exhibited for the colour contributions but should be understood. Here,

$a = \frac{1}{3}$ (eN and μN), $\frac{1}{2}$ $(\nu N, \bar{\nu}N)_{C.C.}$

$b = 0$ (eN and μN), 1 $(\nu N, \bar{\nu}N)$

$\xi = |q^2|/m_U^2$; $x = \frac{1}{\omega} = \frac{|q^2|}{2M_N\nu}$

$v(x)$ = momentum distribution function for any one of the octet of colour gluons within nucleon.

Using momentum conservation [43], one may deduce that the gluons carry nearly 50% of nucleon momentum

$$8\int_0^1 x\, v(x)\, dx \approx 0.5 \quad .$$

The shape of the gluon distribution function $v(x)$ is largely unknown at present. Eventually this fundamentally important function can be determined experimentally (for the case of physical colour) by a study of (σ_L/σ_T)

for asymptotic $|q^2| \gg m_U^2$, at which (σ_L/σ_T) is proportional to $xv(x)$ (see expression below). Pending such a study of (σ_L/σ_T), however, one might need an extensive fitting of eN, μN, νN and $\bar{\nu}$N data (i.e. a fitting of the scaling violations and other anomalies observed in these processes, which may naturally be ascribed to colour gluon excitation) for various assumed forms of $v(x)$. (This would be in the same spirit as the determination of the sea distribution $\bar{q}(x)$, which also is not completely known at present for very small x.)

As a first plausible guess, one may assume that the gluon distribution $v(x)$ has a shape more like that of the sea rather than that of the valence. However, to get a feel for the variation of the gluon effects on colour production, we present results [18] on the rise in structure functions due to colour production for two assumed shapes [44] for $v(x)$:

Model I: $v(x)$ has a shape like that of the sea,

Model II: $v(x)$ has a shape like that of the neutron valence quark within the proton.

Subject to the condition $8\int_0^1 x\, v(x)\, dx = 0.5$, we then obtain (taking some typical values of x):

	Model I $(xv(x))$ (sea like)	Model II $(xv(x))$ (valence like)
$x = 0.5$	≈ 0.01	≈ 0.04
$x = 0.2$	≈ 0.05	≈ 0.1
$x = 0.0$	≈ 0.65	≈ 0.11

Rise in structure functions due to colour production

Subject to the above two models and using the parton model expression for F_2 listed above, we present numerical values for (F_2^{col}/F_2^{flav}) for ep scattering for two typical values of x and two values of $\xi = |q^2|/m_U^2 = 3$ and 5, where one might assume that the scale threshold factor $\rho_{colour}(q^2,\nu)$ has reached its scaling weight unity (see Fig.2):

		MODEL I ($x\gamma(x)$ sea-like)		MODEL II ($x\gamma(x)$ valence-like)	
		$\xi = 3$	$\xi = 5$	$\xi = 3$	$\xi = 5$
$\left[\dfrac{F_2^{col}(ep)}{F_2^{flav}(ep)}\right]$	$x = 0.5$	0.14	0.10	0.25	0.18
	$x = 0.2$	0.20	0.14	0.30	0.20

The following qualitative features of colour contribution to structure functions are worth noting:

(i) While quark parton contributions to colour production dies out quickly with increasing $|q^2|$ due to the (gauge) damping factor $(1 + |q^2|/m_U^2)^{-2}$, the gluon contribution to F_2 survives asymptotically and it scales. From the expression listed, we see that

$$F_1^{col}(eN,\nu N) \xrightarrow{|q^2| \gg m_U^2} 0$$

$$F_2^{col}\begin{pmatrix} eN \\ \nu N\end{pmatrix} \xrightarrow{|q^2| \gg m_U^2} \begin{pmatrix} 1/3 \\ 1/2 \end{pmatrix} xv\,(x) \quad .$$

(ii) Importance of non-leading terms in gluon contribution: One crucial feature of the gluon contribution to colour structure functions is that the non-leading scale violating terms (which are of purely kinematic origin) are associated with large coefficients relative to the leading (scale invariant) terms. As a result, first of all, they lead to sizable scaling vioaltions ($\sim$ 10 to 20%, see table above) in the semi-asymptotic region, which extends up to fairly large $\xi = |q^2|/m_U^2$ of order 10. For example, using the expressions above, we see that:

$$F_2^{\text{colour gluons}} \propto \left\{\frac{3+\xi}{(1+\xi)^2} + \frac{\xi^2}{4(1+\xi)^2}\right\}$$

$$= \left\{\frac{2}{9} + \frac{25}{144}\right\} \approx 0.40 (\xi = 5)$$

$$= \left\{\frac{13}{121} + \frac{25}{121}\right\} \approx 0.31 (\xi = 10)$$

$$F_1^{\text{colour gluons}} \propto \overbrace{\frac{16+4\xi}{(1+\xi)^2}}^{\leftarrow\ \text{non-leading}\ \rightarrow} = \begin{Bmatrix} 1.00 \\ 0.46 \end{Bmatrix} \begin{Bmatrix} \xi = 5 \\ \xi = 10 \end{Bmatrix}$$

Note the importance of the first non-leading term compared with the second (leading term) in F_2 for $\xi = |q^2|/m_U^2$ as large as 10, which corresponds to $|q^2|$ as large as $22(\text{Gev})^2$ for a gluon mass $m_U \approx 1.5$ Gev, or $|q|^2$ as large as $160(\text{Gev})^2$ for gluon mass $m_U \approx 4$Gev. In other words, the approach to scaling of the colour contribution (due to the non-leading colour gluon terms) is extremely slow [18]; the significance of this for νN and $\bar{\nu}N$ scattering is discussed later.

(iii) Nature of scaling violations [7]: Quite clearly, the slow depletion of the non-leading terms should exhibit itself as a scale-violating contribution (above and beyond the log corrections implied by asymptotic freedom [45]) for a large range of $|q^2|$. Note that beyond $|q^2| \gtrsim 2$ to $3m_U^2$ (i.e. $\xi \gtrsim 2$ to 3), where one might expect ρ_{colour} to reach its constant scaling value unity, we would predict that the structure functions (with colour contribution included) should fall with increasing $|q^2|$ before reaching their constant scale invariant values. The inclusion of the log corrections [45] can alter this picture somewhat (especially at low or medium high $|q^2| \lesssim 2m_U^2$). For the low $|q^2|$ region, there is the additional feature that ρ_{colour} (q^2,ν) is increasing from 0 to 1 as $|q^2|$ increases from 0 to $\approx 2\,m_{col}^2$ (see Fig.2). Such an increase in ρ_{colour} would manifest itself as a temporary increase in the structure functions with $|q^2|$ in the low $|q^2|$ ($\lesssim 2\,m_{col}^2$)-region (for Model I (sea-like gluon distribution), such a temporary increase would be prominent only for low x or high ω).

The colour gluon excitation (with sea-like distribution - Model I) may thus provide the basic explanation for the observed [41] decrease in structure functions with increasing $|q^2|$ for low $\omega(\lesssim 5)$ and their increase with $|q^2|$ ($\lesssim 2$ to $3m_{col}^2$) for high $\omega(\gtrsim 6)$, provided the latter turns out to be a relatively low $|q^2|$

temporary phenomenon. There is, of course, the necessary prediction of this explanation that both at low ω as well as at high ω, the structure functions should eventually fall before attaining their scale invariant values

(iv) The ratio σ_L/σ_T: Since there exist charged spin-1 colour gluon partons in our theory, the Callan-Gross relation is violated (i.e. $F_2 \neq 2xF_1$). The gluons manifest themselves most directly through the physical parameter σ_L/σ_T. Using the expressions for F_1 and F_2, we obtain:

$$\frac{\sigma_L}{\sigma_T} = \frac{F_2^{ep} - 2x\,F_1^{ep}}{2x\,F_1^{ep}} \xrightarrow[|q^2| \to \infty]{} \frac{\frac{1}{3}\,x\,v(x)}{\sum\limits_{p,n,\lambda,c} x(q_i(x) + \bar{q}_i(x))\,Q^2_{flav}(q_i)}$$

Thus there is the uncomprising prediction[7),38)] in our theory that $(\sigma_L/\sigma_T) \neq 0$ and asymptotically it must scale. We stress that the above scale invariant asymptotic value of (σ_L/σ_T) is not reached until $\xi = |q^2|/m_U^2 \gtrsim 15$ (for reasons discussed above). Substituting some typical values of $x = 0.1, 0.2, 0.5$ and $\xi = |q^2|/m_U^2 = 2,3,5$ we find (σ_L/σ_T) lying between 0.1 and 0.3 (for either Model I or Model II), consistent with the data. If gluons have a sea-like distribution (Model I), (σ_L/σ_T) should become fairly large (≈ 0.4 to 0.6) at very small $x \lesssim 0.04$ (i.e. $\omega \gtrsim 25$) with $|q^2| \gtrsim 2$ to $3\,m^2_{col}$. It should, in this case, increase with decreasing x for fixed $|q^2|$ – a feature which also seems to be indicated by the data[46)]. To repeat, accurate measurement of σ_L/σ_T at high $|q^2|$ and $M_N\nu$ (especially with $\omega \gtrsim 10$) is of crucial importance in making an unambiguous choice between the gauge theory of physical colour (integer-charge quarks) and unphysical colour (fractionally charged quarks).

(v) Colour excitation by e^-e^+ annihilation: Just as for space-like processes, lepto-production of colour by time-like processes ($e^-e^+ \to X_{col}$) occurs through the intermediary of photon as well as the gluon U; the corresponding production cross-section acquiring once again the gauge kinematic factor $\Delta^2 = (-m_U^2/(q^2 - m_U^2))^2$ with $q^2 > 0$. This time the Δ^2 factor provides a damping only for $q^2 > 2m_U^2$. For $q^2 < 2m_U^2$, on the other hand, it acts as an enhancement.

Using either a light mass ($m_U \approx 1$ to 2 GeV), or a heavy mass gluon ($m_U \approx 4$ GeV) and assuming that gluons are the lightest colour octet states it is possible to show[7)] that the net production of colour continuum is not

unduly enhanced in the region $q^2 < 2m_U^2$ due to the limited number of channels available (above gluon threshold) and the meagre phase space associated with them.

For $q^2 \gg m_U^2$, colour production due to colour part of quark parton charges vanishes (barring renormalization group effects, which may be important at truly asymptotic energies). Thus asymptotically even integer-charge quark partons behave just the same way as fractionally charged quark partons for e^-e^+ as well as eN and μN. This is the novel feature of the gauge approach[1)] to physical colour. Specifically the contribution from the quark partons of the i^{th} type to the R parameter for e^-e^+ annihilation (neglecting log corrections) is given by:

$$R(q_i,\bar{q}_i) = \left| Q_{flav}(q_i) + \left(\frac{-m_U^2}{q^2 - m_U^2}\right) Q_{col}(q_i) \right|^2 \xrightarrow{q^2 \to \infty} Q^2_{flav}(q_i) \quad ,$$

where $Q_{flav}(q_i)$ and $Q_{col}(q_i)$ denote, respectively, the flavour and colour charges of the i^{th} quark. Thus, depending upon the mass of the quark and that of the gluon, as well as q^2, the interference between $Q_{flav}(q_i)$ and $Q_{col}(q_i)$ can lead to interesting behaviour for the production of a quark pair of the i^{th} type above $q^2 > 4m^2_{q_i}$. Note.

$$\sigma(q_i\bar{q}_i) = R(q_i\bar{q}_i)\,\left|f_{q_i q_i \gamma}(S)\right|^2\,\sigma(\mu\bar{\mu}) \quad .$$

The charged gluon parton contribution to colour production by e^-e^+ survives asymptotically in a scale-invariant manner (as for eN). Specifically the quark and gluon parton contributions to R are:

$$\begin{aligned} R &\equiv \sigma(e^-e^+ \to \text{hadrons})/\sigma(e^-e^+ \to \mu^-\mu^+) \\ &= \left\{ \sum_{q_i} Q^2_{flav}(q_i) \right\} + (1-\xi)^{-2} \left[\frac{2}{3}\,(\text{no. of quark flavours}) \right. \\ &\qquad \left. + \left(\frac{1}{8}\right) \left(1 - \frac{4}{\xi}\right)^{3/2} (12 + 20\xi + \xi^2) \right] \end{aligned}$$

where $\xi = |q^2|/m_U^2$. Thus

$$R \xrightarrow[q^2 \to \infty]{} \sum_{q_i} Q^2_{flav}(q_i) + \frac{1}{8}$$

Note that the asymptotic value of R_{col} is reached extremely slowly once again due to contributions from the non-leading colour gluon terms. For example, even at $\xi = |q^2|/m_U^2 = 10$, $R_{col} \approx 0.27$ (whereas asymptotically $R_{col} \approx 0.12$). If gluons are light ($m_U \approx 1$-2 GeV), we would expect R_{col} at SPEAR energies especially for $q^2 \gtrsim 25$ (GeV)^2 to be rather tiny ≈ 0.25 + (log corrections). In this case noting that R_{flav}(GIM) = 10/3 + (log corrections), the net value of R with the basic 16-plet of fermions is: R = (10/3) + (0.25) + log-corrections ≈ 4, which is nearly one unit less than the observed value possibly suggesting the need for new flavour (outside of GIM) or heavy lepton, if we follow the by now commonly accepted criterion.

Noting, however, that the approach to scaling especially in the time-like region is a complicated dynamical question due to opening of resonant thresholds, we wish to defer judgment on the need for new flavours (in addition to GIM) on the basis of the value of R alone (for the case of light gluon) until such time as the asymptotic value of R is better known. (As indicated earlier, if new flavour(and/or heavy lepton) would be needed to account for R or the spectroscopy of the J/ψ-like particles, we will propose to place them within a new sixteen-fold, which arise within some of the variants [9),1)] of the basic model; however the need for them (on the basis of the value of R alone) in our opinion is not yet compelling, since the other new phenomena, encountered in νN and $\bar{\nu}N$, can be attributed to excitation of colour (see below) instead of new flavour).

If gluons are heavy ($m_U \approx 4$ GeV) on the other hand, R_{col} can be sizable at SPEAR energies (E_{CM} = 4 to 8 GeV), its variation depending on the gauge factor $\Delta^2 = (m_U^2/q^2 - m_U^2)^2$ as well as, in this case, upon the opening of new colour thresholds in the 4-6 GeV region.

(vi) Colour excitation in νN and $\bar{\nu}N$:[7),8)] Colour is not over-bright in νN and $\bar{\nu}N$, analogous to eN and μN, since there is the same damping factor $\Delta^2 = [m_V^2/(|q^2| + m_V^2]^2$ in all four cases for colour production: the corresponding expressions for the structure functions are listed earlier; these determine the cross-sections which are:

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 ME}{\pi}\left[F_2(1 - y + \frac{y^2}{2}) + \frac{y^2}{2}(2xF_1 - F_2) \mp (y - \frac{y^2}{2})xF_3\right].$$

Since colour current is vector, it of course, contributes symmetrically to νN and $\bar{\nu}N$ scatterings if the kinematic variables are the same in both cases (i.e. $F^{col}_{1,2}(q^2,\nu)_{\nu N} = F^{col}_{1,2}(q^2,\nu)_{\bar{\nu}N}$, while $F_3^{col}(q^2,\nu) = 0$ for νN and $\bar{\nu}N$). From this it might appear that colour production, even though operative, is not likely to explain the sharp rise in $\sigma_{\bar{\nu}}/\sigma_\nu$, $\langle y \rangle_{\bar{\nu}}$ and the so-called high y anomaly observed above about 50 GeV incident $(\nu,\bar{\nu})$ energy. (In particular, asymptotically colour contribution survives only through F_2 which gives (1-y) distribution vanishing at high y.) However note the following:

1) First, since the flavour currents are chiral and, therefore, their contributions to νN and $\bar{\nu}N$ scatterings differ drastically (e.g. neglecting the sea contribution, one has $(\sigma_{\bar{\nu}}/\sigma_\nu)_{flavour} \sim 1/3$ and $(d\sigma/dy)_{flavour} \propto 1$ and $(1-y)^2$ for νN and $\bar{\nu}N$, respectively); the relative importance of colour versus flavour contribution is quite different for $\bar{\nu}N$ from that for νN (even if the colour contribution were the same in absolute magnitude in both cases at a given incident energy).

2) Second, it is an empirical fact that average $\langle q^2 \rangle$ for $\bar{\nu}N$ is about half that for νN at a given incident beam energy

$$\langle q^2 \rangle_{\bar{\nu}N} \approx \left(\frac{1}{8} \text{ to } \frac{1}{10}\right) M_N E_{\bar{\nu}}$$

$$\langle q^2 \rangle_{\nu N} \approx \frac{1}{5} M_N E_\nu$$

a fact which has its theoretical basis, once again, in differing contributions from the chiral flavour currents to $\bar{\nu}N$ and νN. If we now recall our remarks about the relative importance of the non-leading colour gluon contributions compared with the leading term for $\xi \equiv |q^2|/m_U^2 \lesssim 10$, we see two things:

(a) First, using the empirical $\langle q^2 \rangle$ for νN and $\bar{\nu}N$; as noted above,[47)] the non-leading colour gluon term is expected to be important for νN scattering for

$$E_\nu \lesssim (10 \times 5)\ (m_U^2/m_N) = 100 \text{ GeV for } m_U = 1.5 \text{ GeV},$$

while they are expected to be important for $\bar{\nu}N$ scattering for:

$$E_{\bar\nu} \lesssim (10 \times 10)\ (m_U^2/m_N) \approx 200\ \text{GeV for } m_U = 1.5\ \text{GeV}\quad .$$

For a heavier gluon, they would be important for energies higher still. In other words, even for a light mass gluon, they are important for both $\bar\nu N$ and νN at Fermilab energies.

(b) Second, being non-leading in q^2, the lower the average $\langle q^2\rangle$ (subject to the scale threshold condition $\langle q^2\rangle \gtrsim 2$ to $3\ m_U^2$), the more prominent they are. Given that average $\langle q^2\rangle$ for $\bar\nu N$ is about a factor of 2 lower than average $\langle q^2\rangle$ for νN at the same incident energy, it then follows that <u>the colour contribution from the non-leading terms is far more important in absolute magnitude for $\bar\nu N$ than they are for νN at the same projectile energy</u> (as long as $\langle q^2\rangle$ lies in the semi-asymptotic region; i.e. $\langle\xi\rangle \equiv \langle q^2\rangle/m_U^2 \lesssim 10$). Note thus that this discrepancy (between $\bar\nu N$ and νN) arises in spite of the symmetry between $F_i^{col}(\nu N)$ and $F_i^{col}(\bar\nu N)$ simply due to differeing average $\langle q^2\rangle$ for νN versus $\bar\nu N$, which in turn has its origin (as stated before) from differing contributions from the chiral flavour current to νN versus $\bar\nu N$. This is the essence why colour contribution is <u>a priori</u> expected to lead to a sizable rise [48] in $(\sigma_{\bar\nu}/\sigma_\nu)$ above colour threshold in a semi-asymptotic manner. Such a rise in $(\sigma_{\bar\nu}/\sigma_\nu)$ should, however, be followed by a <u>fall</u> with increasing energy, when non-leading terms become unimportant. Asymptotically (for $|q^2| \gg m_U^2$) we expect

$$\left(\frac{\sigma_{\bar\nu}}{\sigma_\nu}\right)_{c.c} \xrightarrow{|q^2|\to\infty} \frac{\int_0^1 dx\, x\left[\sum_{\text{flavours}}\left[q(x)+3\bar q(x)\right]+\frac{1}{4}v(x)\right]}{\int_0^1 dx\, x\left[\sum_{\text{flavours}}\left[3q(x)+\bar q(x)\right]+\frac{1}{4}v(x)\right]}\quad .$$

Since $8\int^1 x\, v(x) \approx 0.5$, the above asymptotic ratio of $(\sigma_{\bar\nu}/\sigma_\nu)$ (with the gluon contribution included) differs little (by less than 10%) from its asymptotic flavour value (which is ≈ 0.4 for the simple GIM flavours). However, in the non-asymptotic region, the effect of the colour contribution is quite dramatic (see below).

(c) <u>$\langle y\rangle_{\bar\nu}$ and high y anomaly in $\bar\nu N$</u>: The remarks made above with regard to semi-asymptotic rise in $(\sigma_{\bar\nu}/\sigma_\nu)$ applies also to the $\langle y\rangle_{\bar\nu}$ and the y distribution for $\bar\nu N$. This may be seen as follows. Although asymptotically only F_2^{col} survives, which leads to $(1-y)$ distribution, non-asymptotically F_1^{col} is important; this provides a <u>y^2 term</u> in the y distribution (multiplied, of course, by scale violating q^2 dependent term in F_1^{col}). In turn this provides a <u>high y component</u> in the y distribution which should be relatively much more important for $\bar\nu N$ than for νN, both because the non-leading terms are more important for the former than for the latter and also because the flavour current leads to a nearly vanishing cross-section for $\bar\nu N$ at high y. (but not for νN). Thus we would expect a significant (once again semi-asymptotic) rise in $\langle y\rangle_{\bar\nu}$ above colour threshold due to colour production.

The variation in the y distribution (above colour threshold) as a function of x is dependent crucially on the shape of the gluon distribution function $v(x)$. If this distribution is strictly sea-like, the high y component for $\bar\nu N$ (mentioned above) would, of course, be prominent only at small x. However, there is <u>a priori</u> no strong reason for $v(x)$ to be strictly sea-like (as stressed earlier [44]). Note that the predictions on the gross properties such as $(\sigma_{\bar\nu}/\sigma_\nu)$ and $\langle y\rangle_{\bar\nu}$ are not expected to be sensitive to the <u>shape</u> of $v(x)$.

We thus see that the colour contribution has at least all the qualitative ingredients [49] to account for the observed new features in νN and $\bar\nu N$ physics, in particular the rise in $(\sigma_{\bar\nu}/\sigma_\nu)$ and $\langle y\rangle_{\bar\nu}$ as <u>semi-asymptotic phenomena</u>. These points have been examined recently in some detail by Sidhu, Mohapatra and Pati [8] with the assumption that the gluon distribution function $v(x)$ is sea-like.[50] Subject to this assumption (which eventually can be checked most directly from measurements of σ_L/σ_T), their calculation has essentially only one parameter, namely the mass of the charged colour gluons. Their results for $(\sigma_{\bar\nu}/\sigma_\nu)_{c.c}$ and $\langle y\rangle_\nu$ and $\langle y\rangle_{\bar\nu}$ are given in Figs. 3 and 4, respectively.

For comparison the fit by Barger, Phillips and Weiler [51] using b quarks and V + A currents is also plotted. The best fit using new flavours is obtained with a mass of b quarks ≈ 5 GeV (the t quarks forming the other member of the doublet containing b quarks must have a mass as high as ≈ 10 GeV). The colour fit (with no new quarks besides GIM) is perhaps equally as acceptable (if not better) as the new (V + A) flavour fit. The important point to emphasise is that eventually [52] the colour contribution will fall with $F_1^{colour} \xrightarrow[q^2 \to \infty]{} 0$ and $F_2^{colour} \xrightarrow[q^2 \to \infty]{} \frac{xv(x)}{2}$, while the contribution from new flavours will continue rising up to their scale invariant values. This is a characteristic difference which only further experiment (for example for $\sigma_{\bar{\nu}}/\sigma_{\nu}$ and $\langle y \rangle_{\bar{\nu}}$ can settle).

A further remark is in order. We have presented the results for colour excitation without taking into account the scale violating log corrections implied by asymptotic freedom, applicable to our theory (at least at present energies [53]). As emphasised recently by Altarelli, Parisi and Petronzio [54]) these corrections are rather important for νN and $\bar{\nu}N$. However, with any reasonable values of the effective strong coupling parameter $\alpha_s = \bar{f}^2/4\pi \lesssim 0.5$ these corrections by themselves lead to a value $(\sigma_{\bar{\nu}}/\sigma_{\nu}) \leq 0.45$ at $E_{\nu,\bar{\nu}} = 100$ GeV, which is perhaps too small to account for the data. Thus it seems to us that a new excitation (beyond GIM flavours) is suggested by the data. It is entirely conceivalle that the inclusion of the log corrections together with colour excitation (as suggested here) may lead to an improved agreement of theory versus experiment compared with that exhibited in Figs. 3 and 4. This is worth investigating.

(vii) The three central ideas - their non-negotiable consequences:

Before we turn to a discussion of exact versus partial confinement, we wish to list once again the three central ideas, which we have proposed so far. They are:

(A) Lepton-hadron unification within the gauge framework, so that beyond some energy and momentum transfer (10^5 GeV in the basic model), their interactions become similar;

(B) Baryon-lepton number violation;

(C) and unconfined quarks, gluons and all colour as opposed to their exact confinement. We have been able to propose and sustain this third hypothesis in spite of the non-appearance of quarks in standard experimental searches because the lepton-hadron unification hypothesis within the gauge approach led firstly to (i) integer-charges for quarks together with gauge damping for lepto-production of colour, and secondly, (ii) to non-conservation

of baryon and lepton numbers. This second (characteristic) feature implies that even relatively light quarks ($m_q \approx 2$ to 3 GeV) would be short-lived ($\tau_q \approx 10^{-11}$ to 10^{-12} secs. in the basic model) decaying into leptons (or antileptons) without the proton - A THREE-QUARK-COMPOSITE - being too unstable at the same time (see below). This in its turn provides a simple resolution of the MISSING QUARK MYSTERY, until such times as experiments designed to search for quarks decaying into leptons (or antileptons) (see tables III and IV) deny (or prove) their existence.

Quite clearly the lepton-hadron unification hypothesis may be realized in a variety of alternative ways. It would be quite pretentious of us to conceive that we have found the group and the multiplet. But are there then still some crucial and non-negotiable consequences of our central ideas. We find that there are at least three which fall into this category and which deserve experimental attention:

(1) Unconfined colour-gluons which manifest themselves most directly through (σ_L/σ_T), which asymptotically must remain non-zero and scale [7),38)].

(2) Integer-charge quarks decaying [55]) into leptons (or antileptons depending upon the model. One place to look for these decaying quarks is to fix on lepton versus antilepton ratio in NN-collisions; the most direct way to search for them with lifetimes $\approx 10^{-11}$ to 10^{-12} secs. being measurements in emulsions. Their pair production cross-section at the highest accelerator energies should be in the range of 10^{-30} to 10^{-32} cm^2 assuming that their masses are in the range of 2 to 3 GeV. Last, but not the least;

(3) The unstable proton. Since there are no stable quark in the model, the proton must eventually decay into leptons + mesons. As long as quarks and diquarks are heavier than the proton, the proton - a three-quark composite - can decay only provided all three quarks decay "simultaneously" into leptons (or antileptons); this implies that the proton is extraordinarily long lived ($\tau_{proton} \approx 10^{29}$ to 10^{32} years) consistent with its present life-time estimates [56]), but not absolutely stable.

V. CONFINEMENT: EXACT OR PARTIAL

In these lectures, our major battle has been against the Dogma of exact confinement - with a minor side skirmish against new flavours and right-handed currents[57]. We wish to consider the present theoretical status of the Dogma further, but before we do this, we summarize the three points of view about flavour and colour quantum numbers which are currently entertained (see Table V).

Consider the Dogma of exact confinement. There is no question but that quark dynamics has its peculiar features. It is our contention, however, that these peculiarities can be understood in terms of partial confinement so far as integer charge quarks are concerned. Thus, from parton model we may infer that quarks, inside a nucleon behave as if they were free, light particles, and further that if a hadron does dissociate into quarks, there appears to be a large probability of quark recombination into known hadrons. The question is: do these peculiarities really necessitate the DOGMA? The (integer-charge) quarks may be special but are they that special?

In this context let us recall that there are other well known and well understood situations (e.g. electrons in a metal or nucleons in nuclear shell model) when particles moving inside certain environments appear to behave as if they were free - the fact that they should in all reason be experiencing fairly significant interactions from their neighbours showing itself mostly in a change in their effective masses. For quarks too the dynamical reason for their peculiar behaviour is known. It lies in the beautiful discovery of asymptotic freedom associated with the gauge theory of colour gluons. One must, however, emphasise that asymptotic freedom nowhere calls for exact confinement, and certainly not for zero-mass gluons. (It is a standard fallacy in the subject that asymptotic freedom is always ruined by the introduction of Higgs-Kibble particles needed for giving vector gluon a mass.[53])

We believe that a combination of asymptotic freedom associated with coloured gauge gluons plus soliton-like classical solutions for scalar fields (producing space-dependent non-zero expectation values for these scalars) suffices to yield a partial confinement picture of quarks and gluons. The effective masses of these particles outside the nucleon environment are larger than their masses inside, but not infinite.

Ours is a picture which may resemble the MIT bag, except that our bag for hadrons is pervious and there is a finite transmission probability for light quarks and gluons to emerge from the bag and then acquire their physical masses. We may be wrong in ascribing and hoping for low physical masses (a few GeV) for quarks and gluons and higher colour states, but surely there is nothing in quark dynamics yet, so peculiar as to call for a concept as forbidding as the exact confinement dogma.

Perhaps the chief fascination of the exact confinement hypothesis is the one spelt out by Glashow: "... exact confinement represents the end of the road so far as the concept of 'elementarity' is concerned." From this point of view, for the dogmatic there is nothing more elementary, in the sense of physical particles, than the colour singlet pions, kaons, nucleons etc. Exact confinement is thus the greatest idea in particle physics since the bootstrap; since it will mean the final closing of a chapter in nature's architecture - "Tamam".

But how to implement this idea theoretically? There was the hope that Yang-Mills zero-mass gluons would exhibit a highly singular infra-red behaviour, a behaviour so virulent that all S matrix elements involving coloured particles in initial and final states would tend to zero (without violating unitarity), when this (infra-red) singularity would be taken at its face value. Unhappily for this conjecture, it now appears that the infra-red singularities in Yang-Mills theories are no more virulent than those one has encountered from antiquity in QED in perturbation theory[58]. And, in fact, to any given finite order in a perturbation expansion, all infra-red singularities cancel so far as transition probabilities are concerned - in either theory. A naive physicist may be forgiven for believing that either both QED and Yang-Mills theories confine or both do not.

But perhaps one could take refuge behind the inadequacies of perturbation theory. There could be hope that when the perturbation series is summed the sum exhibits a different behaviour in Yang-Mills than in QED. Or alternatively, and more plausibly, exact confinement may be likened to a phase transition which does not manifest itself except when one uses non-perturbative methods. The difficulty with this conjecture is that one does not know of any phase transition phenomenon which is not reversible. When placed in suitable external environments - high temperature, high matter density or high external electric and magnetic fields - all known systems revert from one phase to another. Once again, one is led to contemplate partial rather than exact confinement as the order of quark dynamics.[59)]

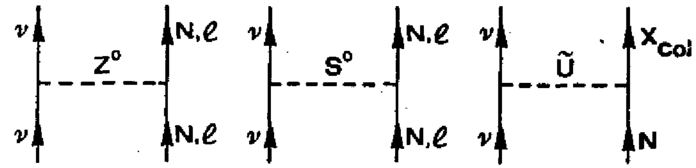
One should not despair, however. There may emerge a most attractive theory of exact confinement for quarks and gluons. Quite clearly in such a theory unconfined leptons cannot be incorporated on par with confined quarks. To have a universal end-of-the-road concept for elementarity, leptons must be assumed to be composites of some more fundamental entities, and it is these entities which might be placed on par with quarks so far as exact confinement is concerned. An alternative suggestion could be that neither leptons nor quarks are confined, but that both are composites of pre-quarks - preons - eight entities, each carrying just one of the four (GIM) flavours or just one of the four colours (red, yellow, blue and lilac). Preons may then be the universal end-of-the-road, to be confined exactly after the theory of exact confinement has emerged.

But however seductive theoretically the idea of exact confinement may appear, and however elegant the final theory of such confinement may be, we respectfully wish to suggest - particularly to our experimental colleagues at the Conference - that the question of exact confinement or not is in the end an empirical one and must be settled by them in the laboratory. Dogmas are absolutely essential for the progress of Science - as Karl Popper has so perceptively emphasised - but they become tragic if they suceed in stopping experimentation designed to prove them wrong.

APPENDIX

Neutral-current interactions in the basic model

In the basic model based on the local symmetry $SU(2)_L \times SU(2)_R \times SU(4)'_{col}$, there are three sources of neutral-current interactions for neutrinos (ignoring superheavy X). These are in the notations of Ref. 1: Z^0, S^0 and $\tilde{U}$:



(i) The Z^0 is identical to the Z^0 of simple $SU(2)\times U(1)$ theory in the leptonic sector, the weak angle being given by $\sin^2\theta_W = g_R^2/(g_L^2 + g_R^2)$, which is nearly $\frac{1}{2}$ for the complete left-right symmetric theory for which $g_L = g_R + \theta(\alpha)$. The Z^0 of the $SU(2)_L \times SU(2)_R \times SU(4)'$ model differs, however, from that of the $SU(2)_L \times U(1) \times SU(3)'_{col}$ model of integer-charge quarks (see first paper of Ref. 1) in the semileptonic sector insofar as production of colour non-singlet states is concerned, the two models still agreeing insofar as production of colour singlet (flavour) hadrons is involved.

(ii) The S^0, arising purely from $SU(4)'$ colour gauging, is coupled to a pure vector $SU(3)$ singlet and $SU(3)'_{colour}$ singlet current (for the variant models which gauge chiral $SU(4)'$ - see Refs. 9 and 11 - there can be vector and axial vector S^0). To be precise its coupling is given by:

$$\frac{f}{2}\left(\sqrt{\frac{3}{2}}\right) S^0_\mu \left[\sum_{\text{all quarks}} \bar{q}\gamma_\mu q - 3\left(\bar{\nu}_e\gamma_\mu\nu_e + \bar{e}\gamma_\mu e + \bar{\mu}\gamma_\mu\mu + \bar{\nu}_\mu\gamma_\mu\nu_\mu\right)\right] .$$

Note the large relative coefficient (-3) for the leptons.

(iii) The contribution from the neutral colour gluon $\tilde{U}$ is important only for colour producing semileptonic neutral-current interactions. (Its contribution to purely leptonic and flavour producing semileptonic interactions are negligible.) Noting the composition of the diagonal field $\tilde{U}$ for the basic gauge model (see Ref. 1), the corresponding amplitude is

$$A(\nu + N \to \nu + X_{col}) = \sqrt{\frac{2}{3}}\left(\frac{G_F}{4}\right)\left[\frac{m_U^2}{|q^2| + m_U^2}\right] \cdot$$

$$\bar{\nu}\gamma_\mu(1+\gamma_5)\nu \left\langle X_{col}\left|J^U_{col}\right|N\right\rangle \quad ,$$

where J^U_{col} is the source of $U^0 = \frac{1}{2}(\sqrt{3}V_3 + V_8)$. Note the emergence of the same gauge damping factor $\left(m_U^2/(|q^2| + m_U^2)\right)$ for neutral-current production of colour by neutrinos as the one we encountered for colour production by charged current νN scattering as well as by eN scattering. The contribution from colour to neutral-current neutrino structure functions may be obtained from those for eN structure functions (given in the text) by simple substitutions. If the charged current νN and $\bar{\nu}N$ anomalies are due to colour production [7,8] as suggested in the text, neutral-current neutrino interactions must also be already potent in producing.

It should be noted that the colour gauge partner of the photon for the $SU(2)\times U(1)\times SU(3)'$ model (see first paper of Ref. 1, where it is called V_{Y0}) differs from the corresponding gauge particle $\tilde{U}$ of the $SU(2)_L\times SU(2)_R\times SU(4)'$ model, since for the former the counter parts of S^0 and W_R^3 (which enter into the photon) are lumped into the single $U(1)$ gauge particle. This would lead to some difference in the phenomenology of colour production by neutral-current interactions for the two models (depending upon the mass of S^0).

The phenomenology of the tripple contribution (from Z^0, S^0 and $\tilde{U}$) to neutral-current interactions involving essentially only two parameters (i.e. $\sin^2\theta_W$ and (f^2/m_S^2)) - the mass of the colour gluon $\tilde{U}$ being constrained already from charged current interactions - is worth investigating. This may provide (assuming that departures from the simple $SU(2)\times U(1)$ model an definitely called for by improved measurements in the near future) yet another signature for colour and should shed some light as to whether S^0 (with its characteristic isoscalar vector coupling) is superheavy (like X) or whether it is relatively light ($\sim 10^3$ GeV).

Table I

Expected properties *) of light neutral colour gluons (mass $\approx$ 1-1.8 GeV).

Decay modes of $\tilde{U} \approx \frac{1}{2}(\sqrt{3}V_3 + V_8)$	Partial width
$\tilde{U} \to e^+e^-$	(2 to 10 keV)
$\to \mu^+\mu^-$	(2 to 10 keV)
$\to \pi\pi\gamma,\ 4\pi\gamma,\ \eta'\gamma$	($\sim$1 to 3 MeV)
$\to 3\pi,\ 5\pi,\ \rho\pi,\ \omega\pi\pi,\ K\bar{K}$	($\sim\frac{1}{5}$ to 5 MeV)
$\to 2\pi,\ 4\pi,\ 6\pi,\ K\bar{K}$	($\sim\frac{1}{10}$ to $\frac{1}{2}$ MeV)

Thus

$$1\ \text{MeV} \lesssim \Gamma(\tilde{U})_{total} \lesssim 10\ \text{MeV}$$
$$\text{B.R.}\ (\tilde{U} \to e^+e^-) \approx (1 \sim 3)\times 10^{-3} \quad .$$

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$$\frac{\sigma(\gamma + N) \to \tilde{U} + X \to e^-e^+ + X)}{\sigma(\gamma + N \to \rho^0 + X \to e^-e^+ + X)} \approx 10^{-2}\left(\frac{1}{5}\text{ to } 5\right) \quad .$$

*) Based on estimates in Ref.[28] It is assumed in Tables I and II that the gluons are the lightest coloured octet mesons. (Most of the remarks (though, in general not all) will apply to the decay modes of whichever is the lightest set.) For a heavier gluon ($m_U \approx 4$ GeV), the decay channels are the same; the expected partial widths will differ. See Ref. 60 for some estimates for this case.

Decay modes of $\tilde{V}$, V^0_{YB} and $\bar{V}^0_{YB}$ in the basic model

	width
$\tilde{V} \approx \frac{1}{2}(V_3 - \sqrt{3}V_8) \to 3\pi,\ 5\pi,\ \rho\pi,\ \omega\pi\pi$	($\sim\frac{1}{5}$ to 5 MeV)
$\to e^-e^+,\ \mu^-\mu^+, \pi\pi\gamma$ etc.	Rates depend on amount of $U^0 = \frac{1}{2}(\sqrt{3}V_3 + V_8)$ in $\tilde{V}$
$\to 2\pi,\ 4\pi,\ 6\pi$	
$\left(V^0_{YB},\ \bar{V}^0_{YB}\right) \to$ "$\tilde{U}$" $_{virtual} \to e^-e^+,\ \mu^-\mu^+$	(B.R. $\sim 10^{-3}$)
$\to \pi\pi\gamma,\ 4\pi\gamma,\ \eta'\gamma$	(dominant modes)
$\to 3\pi,\ 5\pi,\ \rho\pi,$	(dominant modes)

$$\tau(V^0_{YB}) = \tau(\bar{V}^0_{YB}) \ll 10^{-15}\ \text{sec. if}\ \left|m(V^0_{YB}) - m_U\right| \ll m_U \ .$$

Note that V^0_{YB} and $\bar{V}^0_{YB}$ were called V^0_{K*} and $\bar{V}^0_{K*}$ in the past [61].

Table II

Decays of charged colour gluons *)

	$m_V \approx$ 1-2 GeV	$m_V \approx$ 4.1 GeV
$(V^{\pm}_{RB} V^{\pm}_{RY}) \to e^+ \nu_e$	$(30 \pm 5)\%$	$\approx 18\%$
$\to \mu^+ \nu_\mu$	$(30 \pm 5)\%$	$\approx 18\%$
$\to \pi\pi,\ 3\pi,\ 4\pi,\ 5\pi,\ K\bar{K} \cdots$	$(30 \mp 10)\%$	$\approx 54\%$
$\to \pi\pi e\nu,\ K\bar{K}e\nu,\ \eta\eta e\nu$	(1 to 5)%	$\approx$(2 to 10)%
$\nrightarrow \pi e\nu\ ,\ K e\nu\ ,\ \eta e\nu$	forbidden (a)	forbidden (a)

(a) The $\pi e\nu$ and $Ke\nu$ modes are forbidden (relative to the allowed modes) by I-spin and strangeness conservations, respectively. The $\eta e\nu$ mode is forbidden by SU(3) and SU(3)'.

*) Assuming that these are the lightest colour octet mesons.

Table III

Two-body decays of yellow and blue quarks in the basic model ($\Delta B = -\Delta L$)

(see Ref.6 for details)

$p^+_{y,b} \to \nu_e + (\pi,\eta) \quad ; \quad \nu_\mu + K$ (a)

$n^0_{y,b} \to \nu_e + (\pi,\eta) \quad ; \quad \nu_\mu + K$

$\lambda^0_{y,b} \to \nu_e + \overline{K^0} \quad ; \quad \nu_\mu + \eta$

$\quad \to p^+_{y,b} + \pi^- \quad , \quad n^0_{y,b} + \pi^0$ (b)

$c^+_{y,b} \to \nu_e + D^+ \quad ; \quad \nu_\mu + F^+$ (c)

$\quad \to \lambda^0_{y,b} + \pi^+ \quad ; \quad p^+_{y,b} + \pi^0$ (b)

$\tau(y,b) \sim 10^{-11}$ to 10^{-12} sec for $m_q \approx 2$ to 3 GeV (d)

(a) Assuming (μ,ν_μ) are strange. If (e,ν_e) are strange, interchange K's and π's etc.

(b) Normal non-leptonic weak decay; we have not exhibited semi-leptonic weak decays (e.g. $c^+_{y,b} \to \lambda^0_{y,b} + e^+ + \nu_e$), which may have ~10% branching ratio for charmed quarks.

(c) Masses permitting. These modes might be relatively suppressed if D and F are heavy compared with charmed quarks.

(d) $\tau(q_{y,b}) \propto m_q^3$; lifetime estimates include multi-meson emission, which are important; average meson-multiplicity $\approx$ 3 to 4.

Table IV †) *)

Two-body decays of red quarks in the basic model ($\Delta B = -\Delta L = 0$)

Case 1	Case 2	Case 3	Case 4
$m_q > m_V$ $0 < m_r - m_{y,b} < m_\pi$	$m_q > m_V$ $m_r - m_{y,b} > m_\pi$	$m_q < m_V$ $0 < m_r - m_{y,b} < m_\pi$	$m_q < m_V$ $m_r - m_{y,b} > m_\pi$
$p^0_r \to \nu + V^- + \pi^+$ $\to n^0_{y,b} + \gamma$	$p^0_r \to n^0_{y,b} + \pi^0$ (c)	$p^0_r \to n^0_{y,b} + \gamma$	$p^0_r \to n^0_{y,b} + \pi^0$ (c)
$n^-_r \to \nu_e + V^-$ $V^- \to e^-\bar{\nu}_e$ $V^- \to \mu^-\bar{\nu}_\mu$ $V^- \to$ hadrons	$n^-_r \to n^0_{y,b} + \pi^-$ (c)	$n^-_r \to e^- + \bar{\nu}_e + \nu_e$ (d) $\to e^- + \pi^0$ (d) $\to \mu^- + K^0$ (d)	$n^-_r \to n^0_{y,b} + \pi^-$ (c)
$\lambda^-_r \to \nu_\mu + V^-$ $\to p^0_r + \pi^-$ (a) $\to n^-_r + \pi^0$ (a)	same as on left	$\lambda^-_r \to p^0_r + \pi^-$ (b) $\to n^-_r + \pi^0$ (b)	same as on left
$c^0_r \to \lambda^-_r + \pi^+$ (a) $\to p^0_r + \pi^0$ (a) $\to \lambda^0_{y,b} + \gamma$ (b)	same as on left	same as on left	same as on left
$\tau_r \approx 10^{-11} - 10^{-12}$ sec.	$\tau_r \lesssim 10^{-11} - 10^{-13}$ sec.	$\tau(q^-_r) \approx (10^{-11} - 10^{-12}\text{sec})(m_W/m_V)^4$ (e) $\tau(q^0_r) \sim 10^{-11} - 10^{-12}$ sec.	$\tau_r \lesssim 10^{-11} - 10^{-13}$ sec. depending upon $m_r - m_{y,b}$

(cont'd)

Table IV (cont.)

$^{\dagger)}$ Notation: $m_{r,y,b}$ denote masses of red, yellow and blue quarks. $V^{\pm}$ stands for the charged gluons $V^{\pm}_{ry}$ or $V^{\pm}_{rb}$. The lifetime estimates assume quark mass $\approx$ 2 to 3 GeV and include multi-meson-emission, which are important.

(a) Normal non-leptonic weak decays;

(b) Perhaps dominant;

(c) For an extended symmetry[9)] (such as $SU(4)_A \times SU(4)_B \times SU(4)'_A \times SU(4)'_B$), this large factor $(m_W/m_V)^4$ is absent and other decay modes are available.

$^{*)}$ The decay pattern exhibited in these tables has been worked out (Ref.6) following closely the dynamical restrictions of the basic gauge model. See Ref.23 for an indication of certain important alternatives.

Table V

Summary of three approaches to flavour and colour

Flavour	Colour
Standard model (Fractional charge quarks) GIM + new flavours. Need at least one new flavour (b) with a right-handed current to give an explanation of recent νN and $\bar{\nu} N$ data ($m_b \sim 5$ GeV). All J/ψ particles $c\bar{c}$ (and possibly new flavour-anti-flavour) colour singlets.	Dogma of exact colour confinement. Gluons and quarks will never be seen as physical particles. Unified models unite unconfined leptons with confined quarks. Proton unstable, but its lifetime constrained only by experiment. The characteristic energy where leptons and quarks may lose their distinction (except in the matter of confinement) is in excess of Planck energy 10^{19} GeV.
Han-Nambu quarks Nine integer-charge quarks. A satisfactory gauge theory of weak, electromagnetic as well as strong interactions not possible.[36)] At least one quark stable. Alternatively with $\Delta F = 2$, $q \to qqq$ transitions possible so that quarks may eventually decay into the protons which are stable.	All J/ψ particles must be attributed only to colour. No suppression of colour versus flavour-production for eN and μN. This should have led to 100% rise in eN and μN structure functions in contradiction with the data. Similar objections arise from considerations of ($eN/\nu N$) ratio and small value of (σ_L/σ_T).
Our quarks and leptons 12 integer-charge quarks carrying 4 flavours and three colours in the basic model. A gauge theory of all interactions formulated. Lepton-number fourth colour. Quarks decay into leptons ($\Delta F = 0$) or anti-leptons ($\Delta F = 2$). Predict $\ell^-/\ell^+ \neq 1$ in NN, νN etc. through nucleon dissociation mechanism. SLAC (μe) events may be attributed to quark decays provided colour gluons are relatively light ($\approx$ 1 to 1.6 GeV). Proton unstable - the resolution of missing quark dilemma, which requires τ(quark) $\lesssim 10^{-10}$ secs, constrains proton lifetime theoretically (τ proton $\approx 10^{29} - 10^{32}$ years).	Colour shines discreetly in leptoproduction experiments, but quarks and gluons must exist as physical particles. Partial and not exact confinement. J/ψ particles may be ($c\bar{c}$) colour singlets, while (4.1) GeV region may contain colour octet states. Alternatively, the J/ψ (3.1) and ψ' (3.7) may be $c\bar{c}$ colour octets, giving a simple understanding of super-Zweig rule. Colour gauge gluons will give $\sigma_L/\sigma_T \neq 0$ and predict its scaling. Also explain new $\bar{\nu}N$, νN data and its deviation from GIM as due to discrete colour. Predict $\sigma_{\bar{\nu}}/\sigma_\nu$ will rise significantly above GIM value but only temporarily; will fall to nearly re-approach GIM value (within +10%) for $\xi = \langle q^2 \rangle / m_U^2 >> 1$.

TABLE VI

Explanations of phenomena with unconfined versus confined colour gauge theory

NEW PHENOMENA	EXPLANATION WITH UNCOFINED COLOUR GAUGE THEORY	EXPLANATION WITH CONFINED COLOUR GAUGE THEORY
J/ψ family $J^{PC} = 1^{--}$	$\left.\begin{matrix}3.1\\3.7\end{matrix}\right\}(c\bar{c})_{\text{colour-singlet}}\left\{\begin{bmatrix}1\ {}^3S_1\\2\ {}^3S_1\end{bmatrix}\right\}$ Colour within 4-5 GeV and/or in 1-2 Gev region. (If colour in both regions, expect some 4-5 GeV structures should decay into colour in 1-2 GeV region)	Same as left (this picture was proposed here) may need new flavours to explain structures near 4.1
	or, $\left.\begin{matrix}3.1\\3.7\end{matrix}\right\}(c\bar{c})_{\text{colour-octet}}\begin{bmatrix}1\ {}^3S_1\\2\ {}^3S_1\end{bmatrix}$ $(c\bar{c})_{\text{colour-singlets}}$ in 4-5 Gev region. Simple explanation of super Zweig for 3.1 and 3.7 = ("normal" Zweig) x (colour symmetry breaking)	Not permissible
C-even family below 3.1 and between 3.1 and 3.7	Heavy $(q\bar{q})$-spectroscopy	Same as left
$e^-e^+ \to \mu e$ + undetectables	$e^-e^+ \to q_r^- + q_r^+$ 2 step-quark-decay $q_r^- \to e^-\bar{\nu}\nu$, $q_r^+ \to e^+\nu\bar{\nu}$	No explanation unless postulate heavy lepton
$e^-e^+ \to \mu + X$	$e^-e^+ \to V^+ + V^-$ $V^+ \to \mu^+\nu$, $V^- \to e^-\bar{\nu}$ Heavy lepton explanation not needed. Need coloured vector mesons (e.g. gluons) around 1 to 1.6 GeV in the basic model. Suggest search narrow gluon $e^-e^+ \to \tilde{U}$ at Frascati, Novosibirsk, Orsay	
$\nu N \to \mu^-\mu^+ X$	$\nu N \to \mu^- + V^+_{col} + X$ $V^+_{col} \to \mu^+\nu$ (rate $\simeq$ 2 to 4%) as well as $\nu N \to \mu^-$ + charm + X charm $\to \mu^+$ + .. (rate $\approx$ ½ to 1%).	Charm production only; may need new flavours if rate > 1%.

(cont'd)

TABLE VI (cont'd)

NEW PHENOMENA	EXPLANATION WITH UNCOFINED COLOUR GAUGE THEORY	EXPLANATION WITH CONFINED COLOUR GAUGE THEORY
$\nu N \to \mu e K + X$	Charm quark production $\nu + N \to \mu^- + (c + \bar{\lambda}) + X$ $c \to \lambda e^+\nu$, $\lambda \to \nu + K^0$ $\bar{\lambda} \to \bar{\nu} + K^0$ In addition, production of charm meson or baryon	Charm meson or baryon production
$\nu N \to \mu^-\mu^-\ X$	Nucleon-dissociation + associated production of charm and colour (see text). $(\bar{\nu}N \to \mu^+\mu^+)_{\text{dissoc.}} = 0$ (basic model)	Associated production of charm and/or new flavour
Scaling violations eN, μN, νN	Non-asymptotic colour excitation + Log-corrections (asymptotic freedom)	Log-corrections (asymptotic freedom) + New flavour-threshold
$(\sigma_{\bar{\nu}}/\sigma_\nu)_{c.c}$ $\to$ 0.5 to 0.7 $\langle y\rangle_{\bar{\nu}} \to 0.4$	Non-asymptotic colour excitations. At higher energies (if no new flavour excitation except GIM); $(\sigma_{\bar{\nu}}/\sigma_\nu)$ and $\langle y\rangle_{\bar{\nu}}$ should fall to scaling value = GIM + ($\leq$ 10%)	Must postulate "b" quark with mass around 5 Gev. $(\sigma_{\bar{\nu}}/\sigma_\nu)$ and $\langle y\rangle_{\bar{\nu}}$ should continue rising up to their scale invariant values.
$(\sigma_L/\sigma_T) \neq 0$ If it persists	colour-gluon-excitation $\Rightarrow (\sigma_L/\sigma_T) \to f(x) \neq 0$	No explanation
$e^-e^+ \to$ JETS (spin ½ - parentage)	simplest explanation in terms of quark pair production and decay: $e^-e^+ \to q + \bar{q}$ (mostly) $q \to \nu + (\pi, K, \eta)$, $\bar{q} \to \bar{\nu} + (\pi, K, \eta)$ Missing energy carried away by neutrinos	Difficult to see how after a recombination of confined quark anti-quark pairs to make normal hadrons any jet structure can survive.
$NN \to \ell + X$ versus $NN \to \bar{\ell} + X$ ratio $\ell/\bar{\ell} \neq 1$	Two sources of asymmetry between leptons and antileptons: (i) Assoc. production of charmed or coloured mesons and baryons. (ii) Nucleon-dissociation into quarks followed by their decays into leptons ($\Delta B = -\Delta L$), or antileptons ($\Delta B = +\Delta L$).	Only source (i) applies

TABLE VII

A LIST OF ATTEMPTED EXTENSIONS TO THE BASIC MODEL AND OPEN PROBLEMS

Model	No. of Quarks + Leptons	No. of Flavours & Colours	Gauge Symmetry Group	Reason & Characteristics	Weak Features
Basic[1)] $\Delta F = 0$, $\Delta B = -\Delta L$	(12 + 4)	(4, 4)	$SU_L(2)\times SU_R(2) \times SU_C(4)$	$K \to e + \mu$ rate forces characteristic energy beyond which leptons quarks unify, as 10^5 GeV.	1) e,μ distinguished only by strangeness 2) Masslessness of neutrinos achieved but not elegantly. Perhaps need a super-symmetric version of the basic model.
Economical[1)] $\Delta F = 0$, $\Delta B = -\Delta L$	(12 + 4)	(4, 4)	$SU_L(2)\times SU_R(2) \times SU_C^e(4)\times SU_C^\mu(4)$	e,μ distinguished as belonging to different groups $SU_C(4)$ and $SU_C'(4)$ $K \to e + \mu$ forbidden. Thus characteristic energy could be as low as 10^3 GeV.	No elegant explanation of emergence of $SU(4)_{Flavour}$ symmetry; Also Cabibbo angle not computable in principle
Prodigal[1),71)] $\Delta F = 0$, $\Delta B = -\Delta L$	(24 + 8)	(8, 4)	$SU_L'(2)\times SU_R(2) \times SU_C^e(4)\times SU_C^\mu(4)$	Same as above	Weak points of economical model removed; also place for heavy leptons if they exist. However, altogether too rich and prodigal
Mirror[9),62)] $\Delta F = 0$, $\Delta B = -\Delta L$	(24 + 8) $F_{L,R}$ $F'_{R,L}$	(8, 4)	$SU(4)_A \times SU(4)_B \times SU(4)_A^C \times SU(4)_B^C$ Flavour↔colour left↔right Discrete Symm. VECTOR-LIKE Theory, but weak neutral current not pure vector	A single unifying gauge coupling constant. Possibility of skew (V+A)-currents (e.g. $(\bar{P}n')_R$) coupled to lighter W, if needed. Neutrino masslessness can be elegantly implemented.	$K \to e + \mu$ - problem same as for the basic model. Too rich.

(cont'd)

TABLE VII (Cont'd)

For each one of the above models, a version exists,[62)] which gauges ψ_L and the charge-conjugate field ψ_L^C (or equivalently gauges Majorana components of each complex field ψ). In these versions (and introducing new gauge particles) we can implement baryon-lepton number violations, to give the selection rules: (i) $\Delta F = 2$, $\Delta B = +\Delta L$, or (ii) $\Delta B = -\Delta L_e$, $\Delta B = +\Delta L_\mu$ or (iii) $\Delta B = +\Delta L_e$, $\Delta B = -\Delta L_\mu$ (as well as $\Delta F = 2$, $\Delta B = 2$, $\Delta L = 0$), rather than the selection rule of the basic model $\Delta F = 0$, $\Delta B = -\Delta(L_e + L_\mu)$. Though we have listed these minor extensions and variants, we wish to stress that our preference is for the basic model, which is the simplest of all the models considered. It is to be stressed that crucial consequences of our theory

(a) $\sigma_L/\sigma_T \neq 0$ and its scaling behaviour;

(b) the fact of quark decays into leptons or antileptons with short lifetimes and

(c) long-lived but unstable proton ($\tau_{proton} \approx 10^{29}$ to 10^{32} years)

are common features of the basic model as well as all its variants which we have proposed.

Since none except the basic model have been worked out in detail, these who like extra flavours or heavy leptons or quark decays involving $\Delta F = 2$, may wish to explore the consequences of the variants proposed.

We now list some of the open problems of our theory on which further work would be most welcome.

(1) A detailed model of partial confinement and Archimides effect, from which one can compute the spectrum of expected colour states, and the probabilities for nucleon-meson-dissociation into quarks versus quark re-association to form normal hadrons.

(2) Using such a model, need an estimate of multiplicities, distributions with momentum transfer and jet structure of secondaries in high-energy collisions.

(3) We need an estimate of prompt leptons versus anti-lepton ratio from normal (charm and colour) associated production and the expected ratio from nucleon dissociation mechanism into quarks and their subsequent decays to facilitate the experimental search for asymmetries in lepton versus anti-lepton production in NN etc.

(4) Need an examination of colour effects in νN, $\bar{\nu} N$, eN, μN making different hypotheses for the gluon distribution function $v(x)$ and also investigation of the effects of incorporating log corrections expected from asymptotic freedom for the parton-model formulae for flavour + colour excitation (presented here).

REFERENCES AND FOOTNOTES

1) J.C. Pati and Abdus Salam, Phys. Rev. D8, 1240 (1973); Phys. Rev. Letters 31, 661 (1973); Phys. Rev. D10, 275 (1974).

2) Of course, some day the theory must also explain what determines the characteristic energy at which the distinction between weak and electromagnetic forces disappears on the one hand and strong and weak and electromagnetic on the other.

3) S. Brodsky and J. Sapirstein, (to be published).

4) M.L. Perl et al., Phys. Rev. Letters 35, 1489 (1975).

5) G. Hanson et al., Phys. Rev. Letters 35, 1609 (1975).

6) J.C. Pati, Abdus Salam and S. Sakakibara, Phys. Rev. Letters 36, 1229 (1976).

7) J.C. Pati and Abdus Salam, Phys. Rev. Letters 35, 11, (1976); J.C. Pati, Lectures presented at the Conference on Gauge Theories and Modern Field Theory held at Northeastern University on 26 September 1975 (published by M.I.T. Press) at the Coral Gables Conference, University of Miami, January 1976, and at the American Physical Society meeting held in Washington, D.C. (April 1976); Abdus Salam, Lecture delivered at CERN (March 1976), ICTP, Trieste, preprint IC/76/21.

8) D.P. Sidhu, R.N. Mohapatra and J.C. Pati, Brookhaven Preprint (June, 1976).

9) An independent motivation for the existence of a new set of 16 four-component fermions arises if we wish to choose the more symmetrical gauging pattern $SU(4)_A \times SU(4)_B \times SU(4)'_A \times SU(4)'_B$ from the point of view of realizing a unified theory with one coupling constant. In this case, the requirement of freedom from anomalies would suggest the existence of the mirror fermions F' with the mirror-symmetric gauging pattern: $F_{L,R} \leftrightarrow F'_{R,L}$. R.N. Mohapatra and J.C. Pati, Phys. Rev. D11, 2558 (1975); J.C. Pati and Abdus Salam, Phys. Letters 58B, 333, 1975.

10) R.N. Mohapatra and J.C. Pati, Phys. Rev. D11, 2558 (1975) and Ref. 1.

11) Ref. 1 and J.C. Pati and Abdus Salam, Phys. Rev. D11, 1137 (1975).

12) Note that if we admit additional Higgs-Kibble multiplets both S^0 and W_R can be much lighter than 10^5 and 10^4 GeV, respectively, without at the same time lowering the mass of X; this would correspondingly enhance the strength of S^0-induced neutral current interactions and W_R-induced (V+A) interaction in β decay (see Ref.1).

13) A. Benvenuti et al., Phys. Rev. Letters 34, 419 (1975); ibid 35, 1199 (1975); ibid 35, 1203 (1975); ibid 35, 1249 (1975).

14) In the past we used the notations $V^{\pm}_{\rho}$ and $V^{\pm}_{K^*}$ for $V^{\pm}_{RB}$ and $V^{\pm}_{RY}$, respectively.

15) The effective mass of a quark inside a nucleon may be much lighter than its mass outside the nucleon (Archimedes effect).

16) See D.P. Sidhu, J. Smith and J.A.M. Vermaseren (preprint 1976) for reference on these models and their consequences for dimuon production.

17) Adding the rates of $\mu^-\mu^+$ (Ref. 13) and μ^-e^+K events (J. Von Krogh et al., Phys. Rev. Letters 36, 710 (1976)), which cover different kinematic regions and assuming (μ-e) universality, the like-sign dilepton rate appears to be $\gtrsim 2\%$.

18) J.C. Pati, Talk presented at the Northeastern University Conference on Gauge Theories and Modern Field Theory at Coral Gables and at Washington APS Meeting (Ref. 7).

19) If this is indeed the case, we may infer that the lightest charm mass may be somewhat lower than the lightest colour or quark.

20) A number of e^+'s accompanying μ^-'s in νN may also be attributed to the possibility that quark decays may obey $\Delta B = +\Delta L_e = -\Delta L_\mu$ so that charged yellow and blue quark decay into (positrons + mesons) (corresponding to one specific form of Konopinski-Mahmoud model of leptons). Any single accompaniment of positrons by kaons may be understood as due to e's being strange and muons non-strange.

21) See Table I. Note in spite of this small branching ratio a narrow resonant (e^-e^+) signal $\approx 10^{-4}$ expected from U^0 production and leptonic decay should not probably be beyond visibility in a high statistics high resolution study of invariant mass of e^-e^+ pairs produced by (μN) collisions due to the reduction of background. We urge such a search for discovery of $\bar{U}^0$. This should be in addition to searches for $\bar{U}$ through e^-e^+ annihilation photoproduction and search for proving e^-e^+ pairs in NN collisions, as stressed elsewhere.

22) K.W. Chen, Michigan State University preprint (MSU-CSL-33, May 1976).

23) This second restriction is imposed by the dynamics of the basic gauge model and not by the general concept of baryon lepton number violating quark decays (see in particular the second paper of Ref. 1). It is possible to invent variant (and non-gauge) models, where $q_R^- \to (e^-,\mu^-) + \nu + \bar{\nu}$-

three-body decay occurs with a significant rate and branching ratio without the intermediary of the charged coloured gluon. In these lectures, however, we have throughout retained the restrictions imposed by the basic gauge model.

24) Preliminary calculations by B. Kayser, J.C. Pati, S. Sakakibara and G. Zorn for the kinematics of the (μe) events having their origin in two-step quark decays show that the corresponding lepton momentum spectrum agrees well with the present data (as presented by M. Perl at this Conference) particularly with gluons having relatively low mass $\lesssim 1.4$ Gev. These and other kinematic results pointing to distinctions between heavy lepton versus quark hypothesis for the (μe) events will appear in a forthcoming preprint by the above authors.

25) Note that SPEAR data is consistent with a part (say 30 to 40%) of the (μe) events arising from two-body decays, the balance arising from three-body or effective three-body decays (i.e. quark decays) as proposed here.

26) M. Cavalli-Sforza et al., Phys. Rev. Letters, 36, 568, 1976.

27) G.A. Snow, Phys. Rev. Letters, 36, 766, 1976.

28) J.C. Pati, J. Sucher and C.H. Woo, Maryland Preprint 76-120 (June 1976) submitted to 18th International High-Energy Conference, Tbilisi, USSR. The suppression of the $\widetilde{U}$ photoproduction cross-section compared with that of the ρ^0 (by a factor $\sim 10^{-3}$), obtained here, is a special consequence of the gauge origin of photon and $\widetilde{U}$, for which the colour part of the electromagnetic current is essentially the source of $\widetilde{U}$ (except for finite mass renormalization term δm_U^2), so that $\langle 0|J_{em}|\widetilde{U}\rangle = (e/f)\ \delta m_U^2 \epsilon_\mu$, $(\delta m_U^2/m_U^2)$ is calculated to be small.

29) M. Han and Y. Nambu, Phys. Rev. 139, B1006 (1965).

30) D. Politzer, Rochester Talk (June 1976); Harvard Preprint.

31) E. Riordan et al, SLAC-PUB-1634, August 1975; L. Hand, Comments Nuclear Particle Physics 6, 103 (1976); Review by Dree at this Conference.

32) C.H. Llewellyn-Smith; R.P. Feynman and others.

33) See B. Barish, 6th Hawaii Topical Conference in Particle Physics, (August 1975), CALT 68-535 for a value of r and Proceedings of the American Physical Society (Division of Particles and Fields) - Conference held at Williamsburg (September 1974) for a plot of νW_2 as a function of q^2 for the SLAC data. If the effective threshold for colour (W_{col}) lies around 4 GeV, it would be reasonable to assume that at least the lower energy part of MIT-SLAC data corresponding to $E_e \lesssim 20$ GeV involves only colour singlet (flavour) production.

34) See, for example, C.H. Llewellyn-Smith, Proceedings of SLAC - Photon-Hadron Conference, Stanford, California (September 1975). Note that, field-theoretically, unlike new heavy quark-excitation, colour current made out of (p,n,λ) quark fields should "feel" the same effective mass for these quarks inside nucleon as does the flavour current made out of the same quark fields. Thus a very slow rescaling expected for heavy quark excitation is not expected for colour excitation in the Han-Nambu-Model.

35) D. Gross and F. Wilczek, Phys. Rev. D8, 3633 (1973), D9, 980 (1974); H.D. Politzer, Physics Reports 14C, 129 (1974).

36) For the Han-Nambu theory of integer-charge quarks (Case II), on the other hand, colour excitation by neutrinos is possible, but its strength and characteristics are a priori not unique. If one assume phenomenologically that colour and flavour currents contribute symmetrically to the weak charge as they do for the electric charge (as has been proposed in the literature), colour should have shone in νN scattering leading to large $\sim 100\%$ rise in neutrino structure functions at Fermilab energies (if colour threshold $\lesssim 5$ Gev), which would be incompatible with the data. The equally serious problem (with only 9 quarks in the theory) is that the known hadron spectroscopy and the requirement of realising a renormalizable gauge theory of only weak and electromagnetic interactions prevents one from introducing strong interactions altogether (gauge or non gauge) into the theory (J.C. Pati and Abdus Salam, Trieste preprint IC/73/81 (unpublished) and L.B. Okun, Physics Letter, 1973). This applies to some of the recent attempts (e.g. by Feldman and Matthews and by Stech) at building a renormalizable gauge theory of the weak and electromagnetic interactions with 9 Han-Nambu quarks.

37) See for example Review Talk by B.W. Lee (Coral Gables Conference, January 1976) and references therein.

38) G. Rajasekharan and P. Roy, Pramana, Vol 5, No. 6, 303 (1975).

39) This class of gauge theories was first proposed in Ref. 1.

(40) Note that logically m_{col} should not be equated with m_U, especially if the gluons are light (~ 1 GeV). The colour-continuum spectrum may well begin around 2 to 4 Gev, even if gluons are lighter than 2 GeV.

(41) Y. Watanabe et al., Phys. Rev. Letters 35, 898 (1975); C. Chang et al; Phys. Rev. Letters 35, 901 (1975). More recent Fermilab data on $F_2(q^2)$ as a function of q^2 for various $\langle \omega \rangle$ were presented by L. Hand at Trieste Weak Interaction Conference, June 1976. See also similar curve presented by L. Mo at SLAC Conference, August, 1975, and Ref.46.

42) With chiral SU(4)' colour gauging (see Ref. 9) there would be newer possibilities, e.g. lighter vector and somewhat heavier axial vector SU(3)' - colour gauge mesons.

43) C.H. Llewellyn-Smith, Phys. Rev. D4, 2392 (1971).

44) It may well, of course, be that the true solution lies somewhere in-between these two extremes; for example nearly half of the gluon momentum being associated with sea-like and the other half with valance-like distribution.

45) See, for example, D. Politzer (Ref. 30) and W.K. Tung, Phys. Rev. Letters 35, 490 (1975).

46) See Drees' Review Talk at this Conference

47) Here, we are making a simple extrapolation to higher energies for the relationship between $\langle q^2 \rangle$ and $E_{\nu,\bar{\nu}}$, this may need modification for $E_{\nu,\bar{\nu}} > 200$ GeV.

48) For a quick estimate of the order of magnitude expected one may proceed as follows (this is substantiated later by explicit calculation): Without colour production one may choose $\sigma_{\bar{\nu}} \propto 0.4$, $\sigma_\nu \propto 1$. The colour contribution to νN is nearly 15% of flavour (analogous to eN see Table on page 33); thus $\sigma^{col}_{\nu N} \propto 0.15$ (approximately); $\sigma^{col}_{\bar{\nu}N}$ is bigger by about 30 to 40% than $\sigma^{col}_{\nu N}$ due to increased importance of non-leading terms (see earlier discussions); thus expect $\sigma^{col}_{\bar{\nu}N} \propto (\approx 0.2$ to $0.22)$. Hence $\left[\frac{\sigma^{\bar{\nu}N}}{\sigma_{\nu N}}\right]_{flav\,+\,col} \approx \frac{0.4 + (0.2 \text{ to } 0.22)}{1 + 0.15}$ ≈ 0.52 to 0.55.

49) These qualitative remarks were pointed out in Ref. 7; they are founded quantitatively in Ref. 8.

50) The effect of other assumed forms for $v(x)$ on $(\sigma_{\bar{\nu}}/\sigma_\nu)$, $\langle y \rangle_{\bar{\nu}}$ and y distributions for $\bar{\nu}N$ and νN is being studied by these authors.

51) V. Barger, R. Phillips and T. Weiler, Wisconsin preprint (1976).

52) Depending upon m_U, i.e. at $E_\nu > 50\ (m_U^2/m_N)$ and $E_{\bar{\nu}} > 100\ (m_U^2/m_N)$, see estimates in text. Of course the predicted fall is subject to the assumption that no new flavour (apart from GIM) would be excited in the energy regime in the future.

53) As emphasised elsewhere, even if Higs-Kibble fields are treated as elementary and even if the $\lambda\phi^4$ term associated with these fields happen to violate asymptotic freedom, such a loss of asymptotic freedom is not serious at present energies since (for realistic cases with massive colour gluons) one may choose $\lambda \lesssim e$. Note even if gluons are left massless (standard model), in such models at least the W's must be given mass, the corresponding Higgs-Kibble fields would spoil asymptotic freedom (if they do in the above case) at asymptotic energies. On the question of realizing asymptotic freedom in spite of the presence of Higgs fields, see N.P. Chang, Phys. Rev. D10, 2706 (1974) and E.S. Fradkin and K. Kalshnikov, Phys. Letters, 59B, 159 (1975).

54) G. Altarelli, G. Parisi and R. Petronzio, Preprint (Univ. of Rome), see Barnett, Georgi and Politzer (preprint) for a comment on this paper.

55) Okun and Zeldovitch (Comments in Nuclear and Particle Physics, 1975) have remarked that quark decay lifetimes $\approx 10^{-10}$ secs. may imply too rapid a disappearance of nucleonic matter before nucleosynthesis starts in the early stages of the universe. We wish to stress that in the high temperature environment of the early universe the effective rate of baryon-number violation is strongly damped. This rate is controlled by four expectation values $\frac{\langle c_1 \rangle \langle c_4 \rangle}{\langle b_4 \rangle \langle a \rangle}$, where $\langle c_1 \rangle$ is related to the masses of the colour gluons $\langle b_4 \rangle$ to the mass of the X, while $\langle a \rangle$ and $\langle c_4 \rangle$ contribute to W mass. Each one of these vacuum expectation values will make a transition to a zero value at a different temperature of the order of (Higgs potential parameters)$^{\frac{1}{2}}$ times the appropriate expectation values $(\langle c_1 \rangle < \langle c_4 \rangle < \langle a \rangle < \langle b_4 \rangle)$. Assuming the Higgs parameters to be of the order of unity, and since $\langle c_1 \rangle$ is of the order of 1 GeV $\approx 10^{13}\,{}^0$K there is no (or little) baryon-number violation until the Universe is $\sim 10^{-6}$ secs. old. At this epoch gluons are massless, but W's and X's are massive and nucleosynthesis has already occurred. These are order of magnitude estimates and depend upon the parameters of the Higgs potential; but they do point to the importance of taking effects of

temperature (as well as cosmic electric and magnetic fields) into account for spontaneously generated symmetry violations. We stress that the whole matter of the early universe is a very subtle phenomenon. For example, depending upon the nature of the Higgs-potential parameters, quarks may still decay during the transition period ($\approx 10^{-10}$ to 10^{-6} secs), but at rates much much slower than the rate for low temperature environment. These new possibilities involving baryon-lepton-number violation (though rather tiny at high temperatures) may play a significant role in an understanding of what we see today in terms of assumed models of the early Universe.

56) F. Reines and M.F. Crouch, Phys. Rev. Letters 32, 493 (1974).

57) Any new flavours can easily be incorporated in our model, but exact confinement of quarks would deal a blow to their unification with unconfined leptons.

58) T.W. Appelquist, J. Carrazone, H.Kluberg-Stern and M. Roth, Phys. Rev. Letters 36, 768 (1976); E.C. Poggio and H.R. Quinn, Phys. Rev. D (to be published) and Y.P. Yao, Phys. Rev. Letters 36, 653 (1976).

59) There used to be one inexorable confining agency in Physics - the ever-attractive force of gravity - which one thought confined matter in black holes. Unhappily, Hawking and quantum mechanical tunnelling have unseated this agency also from this unique role. It may not be relevant to particle physics, but as one now knows, even black holes radiate when they are forming - they are no longer the inexorably and indiscriminately confining objects they used to be.

60) J.C. Pati and Abdus Salam, Phys. Rev. Letters 34, 613 (1975).

61) V^0_{YB} and $\bar{V}^0_{YB}$ decay by utilizing V^-_{RB}-W^- as well as V^-_{RY}-W^- mixings which (via loop diagrams) lead to $V^0_{YB} \leftrightarrow \tilde{U}_{virtual}$ (see W.R. Franklin, Nucl. Phys. B91, 160 (1975)).

62) J.C. Pati, Abdus Salam and J. Strathdee, Nuovo Cimento 26, 72 (1975).

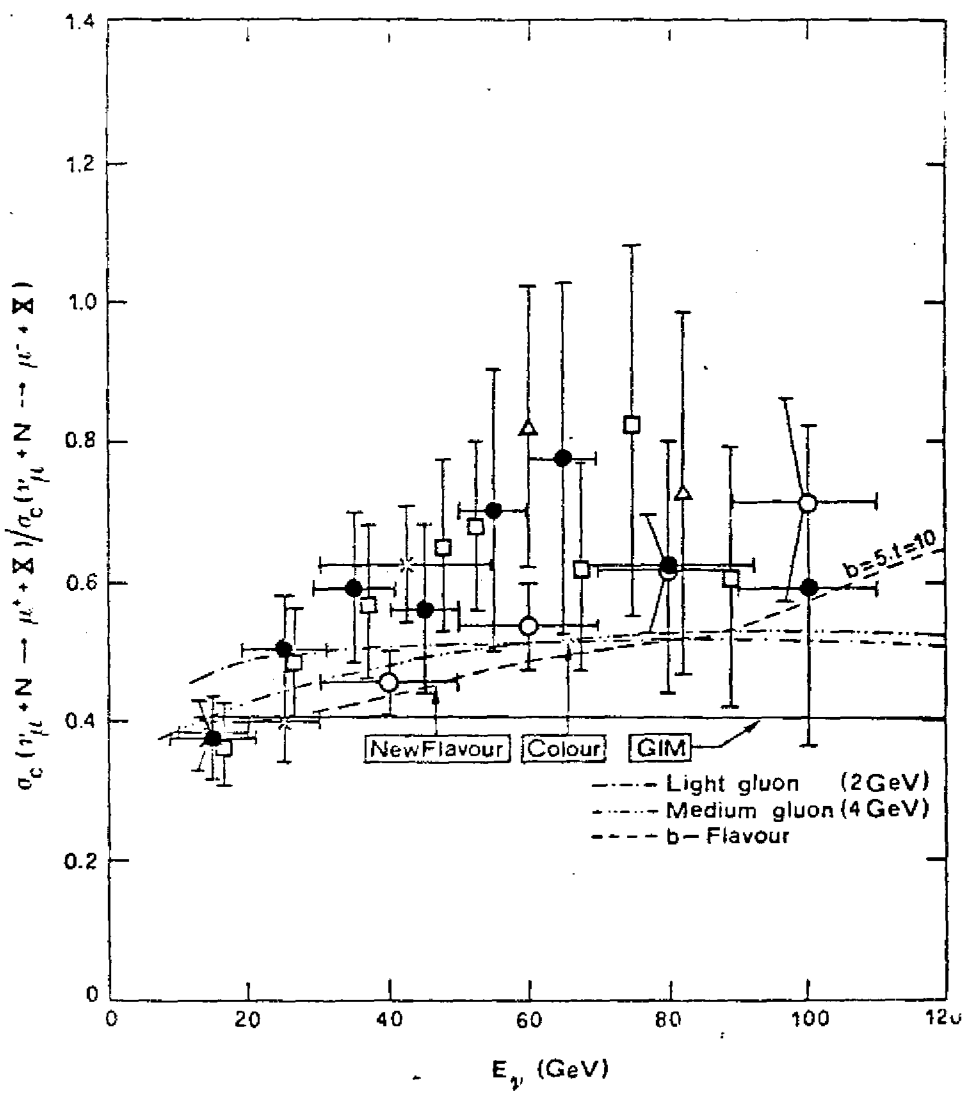

Fig.3

Colour - this includes GIM flavour + quark colour excitations (Ref. 8).
New flavours - Ref. 51.

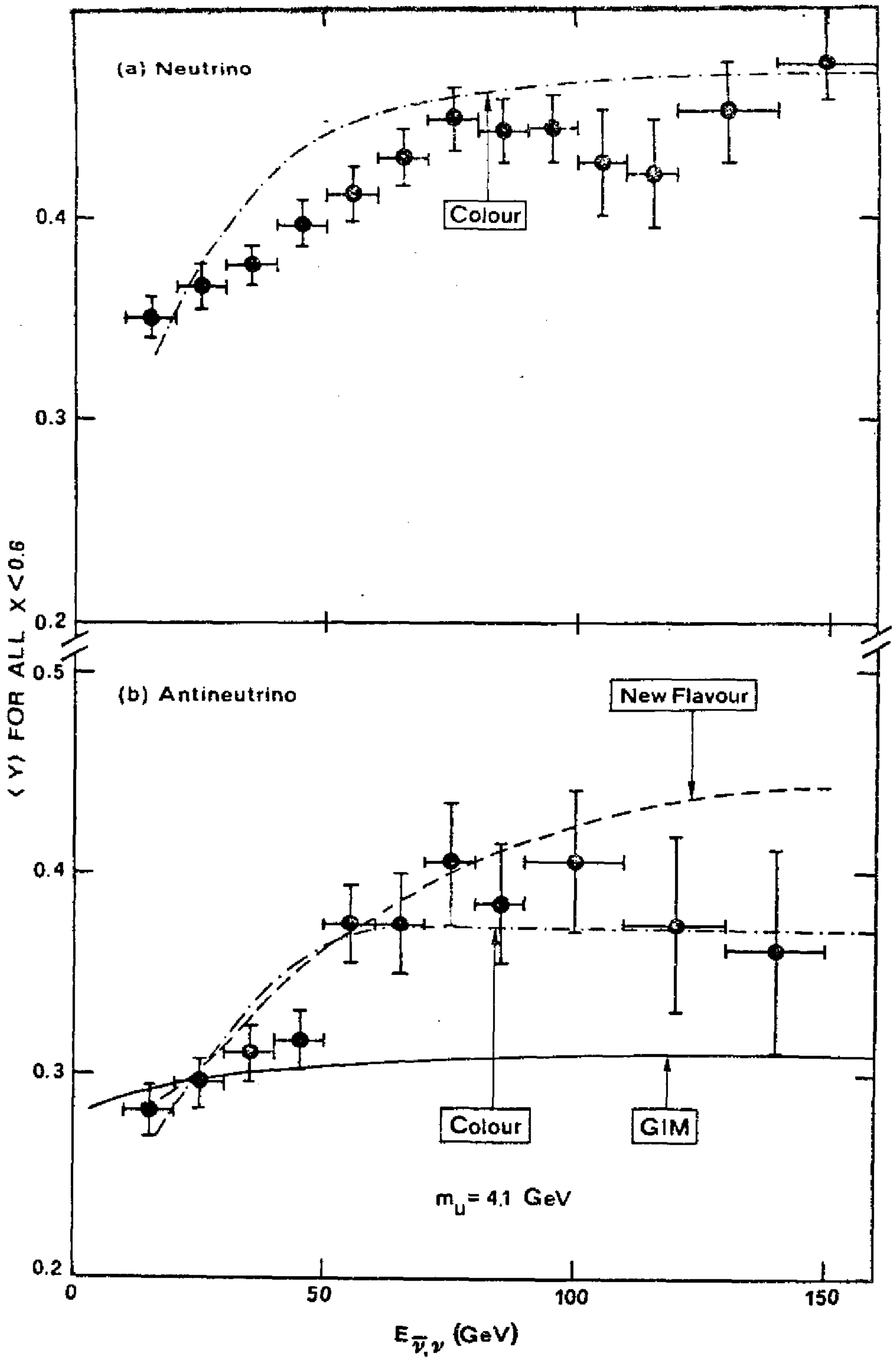

Fig.4

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