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NEW SOURCES OF MULTI-LEPTONS IN ℓN AND ℓ^-/ℓ^+ RATIO IN NN COLLISIONS *

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ABSTRACT

Two new mechanisms for multi-leptons in νN , $\bar{\nu}N$, μN and NN are proposed; these are coloured integer charge gluon decays into leptons and nucleon dissociation into quarks followed by their decay into leptons. The characteristic signal of the latter in the basic model of lepton-hadron unification is like-sign dileptons in νN ; their absence in $\bar{\nu}N$ and deviation of the ratio e^-/e^+ and μ^-/μ^+ from unity in NN collisions.

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1. In the gauge theory 1) of integer charged quarks and coloured 1^- gluons, there are three sources of multi-leptons in νN , μN , NN and e^+e^- experiments. 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).

In a recent letter 2), in collaboration with Sakakibara, we have noted that the μe events observed in e^-e^+ annihilation 3) may have their origin in the pair-production and decays of charged red quarks and light charged colour gluons. In this note, following the same approach, we wish to emphasise a new source of multi-leptons in νN , μN and NN scatterings: namely the DISSOCIATION of nucleons into three valence quarks (with or without excitation of sea quark pairs) followed by quark decays into leptons. Since all quarks in our model decay into (leptons + mesons) - that is, from an experimental point of view, quarks may be considered as "lepton-meson resonances" - this mechanism must evenutally become their most copious source. It is of particular interest to note that (in the basic model) the dissociation mechanism would give rise to like-sign dileptons $(\mu^-\mu^-)$ for νN but no $(\mu^+\mu^+)$ for $\bar{\nu}N$. We point out several tests which should help decide unambiguously whether this novel possibility - nucleon dissociation and quark decay - is already operative in NN and neutrino scattering at present energies. These tests rely on deviations from unity, expected from the dissociation mechanism for the ratio of leptons versus anti-leptons in νN, μN and NN .

In this note we shall mainly be concerned with our basic model 1),4) of a unified theory of leptons and quarks, but the deviations from unity mentioned above hold for all models which unify leptons and quarks. Assign to quarks and lepton pairs (ν_e, e^-), (ν_μ, μ^-) the quantum numbers $B = 1$, $L_e = 1$, $L_\mu = 1$, and define fermion-number F to equal $F = B + L_e + L_\mu$. If quarks decay into leptons + mesons, there are four distinct possibilities for semi-leptonic decays:

$$\begin{array}{lll}
(1) & q \to \ell + \text{meson}\ (\Delta F = 0\ ,\ \Delta B = -\Delta L_{e,\mu}) & \text{— the basic model} \\
(2) & q \to \bar{\ell} + \text{meson}\ (\Delta F = 2\ ,\ \Delta B = \Delta L_{e,\mu}) & \\
(3) & \left.\begin{array}{l} q \to \ell_e + \text{meson} \\ \quad\ \bar{\ell}_\mu + \text{meson} \end{array}\right\} (\Delta B = -\Delta L_e\ ,\ \Delta B = +\Delta L_\mu) & \text{— other possible unified models} \\
(4) & \left.\begin{array}{l} q \to \bar{\ell}_e + \text{meson} \\ \quad \to \ell_\mu + \text{meson} \end{array}\right\} (\Delta B = +\Delta L_e\ ,\ \Delta B = -\Delta L_\mu) &
\end{array}$$

Assume that any given model of quark-lepton unification is such that only one of these decay possibilities occurs, e.g. (3). Now in NN collisions the process of nucleon dissociation into quarks and their subsequent decays will clearly give ℓ_e and $\bar{\ell}_\mu$ signals and no $\bar{\ell}_e$, ℓ_μ signals, leading to over-all $\ell_e/\bar{\ell}_e$, $\bar{\ell}_\mu/\ell_\mu >> 1$ for prompt "direct" leptons[5] (i.e. leptons which do not come from the "trivial" decays of π's, K's, hyperons etc.), so far as this mechanism is concerned.

For the four types of unified theories listed above, the expectations for NN from dissociation of nucleons and subsequent decays of quarks are:

(1) $\ell_e/\bar{\ell}_e$, $\ell_\mu/\bar{\ell}_\mu \gg 1$,

(2) $\ell_e/\bar{\ell}_e$, $\ell_\mu/\bar{\ell}_\mu \ll 1$,

(3) $\ell_e/\bar{\ell}_e \gg 1$, $\ell_\mu/\bar{\ell}_\mu \ll 1$,

(4) $\ell_e/\bar{\ell}_e \ll 1$, $\ell_\mu/\bar{\ell}_\mu \ll 1$.

The net deviation from units of the $(\ell/\bar{\ell})$ ratio would of course depend upon the relative strengths of dissociation versus (non-dissociative [6]) sources of prompt leptons.

To sharpen the ideas, in the rest of this note we concentrate on case (1), i.e. the basic model [1], with $\Delta F = 0$, $\Delta B = -\Delta L$. For this model we have constructed the detailed gauge theory, and for this reason, we can give the detailed predictions for quark decays. (This is not to say that nature may not prefer the other models, (2), (3) or (4), though we harbour a prejudice that this is perhaps unlikely.)

2. In detail and for illustration, the crucial points of the new mechanisms are the following, so far as the basic model with $\Delta F = 0$, $\Delta B = -\Delta L$ is concerned:

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 decay into a charged lepton $(\ell^- + \bar{\nu} + \nu)$.

iii) In the basic model [1] there are no quark decays into (e^+, μ^+) + mesons [6], 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.

3. We list below 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. Since one member $(\sqrt{3}\,V_3 + V_8)/2$ of the coloured gluon octet 7) $(V^{\pm}_{RY}, V^{\pm}_{RB}, V^{0,\bar{0}}_{YB}, V_3, V_8)$ 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 $(m_q \approx 2 - 3$ GeV) or heavy quarks $(m_q \approx 3 \sim 5$ GeV). These are physical masses outside of the nucleon environment.8)

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

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. 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 I. Note the crucial difference between colour and charm - the leptonic branching ratio of colour is larger 9) (by a factor ≈2 to 5), and K's are produced in pairs (not singly) even in semi-leptonic decays.

B. Quark decays

As emphasised in Ref.2 and in Sec. 1, 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 II and III.

In summary, only the charged red quarks can possibly be the source of charged leptons in the basic 1) model with $\Delta F = 0$.

4. 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) $$\begin{array}{l} \nu + N \to \mu^- + D + X \\ \qquad\qquad\quad \hookrightarrow (\mu^+ \text{ or } e^+ + \cdots) \end{array}$$ (charm production ≈10%)

(B) $$\begin{array}{l} \to \mu^- + V^{+}_{\text{colour}} + X \\ \qquad\quad \hookrightarrow (\mu^+ \nu_\mu) \text{ or } (e^+ \nu_e) \end{array}$$ (colour production ≈10 to 15%)

(C) $$\begin{array}{l} \to \mu^- + (D \;\;+\;\; \bar{D}) + X \\ \qquad\quad \swarrow \qquad\quad \searrow \\ (\ell^+ \text{ or hadrons}) \;\; (\ell^- \text{ or hadrons}) \end{array}$$

(D) $$\begin{array}{l} \to \mu^- + (V^{+} \;\;+\;\; V^{-}) + X \\ \qquad\quad \swarrow \qquad\quad \searrow \\ (\ell^+ \nu_\ell \text{ or hadrons})(\ell^- \bar{\nu}_\ell \text{ or hadrons}) \end{array}$$

(E) $$\begin{array}{l} \to \mu^- + (q_r^- \;\;+\;\; q_r^+) + X \\ \qquad\quad \swarrow \qquad\quad \searrow \\ (\nu + \ell^- + \bar{\nu}_\ell) \text{or} \;\; (\bar{\nu} + \ell^+ + \nu_\ell) \text{or} \\ (\nu + \text{hadrons}) \;\; (\bar{\nu} + \text{hadrons}) \end{array}$$

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: 10) $(\mu^-\mu^+$ 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 in accord with the data.10) Contrast this with phenomenological lepto-hadron models, where this feature is not realized. 11)

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

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

which by itself might be too low compared with the data.[12)]

4) Within the gauge theory approach,[1)] parton-model based estimates [13)] 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

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

This larger $(\mu^-\mu^+)$ rate appears to be more compatible with the present data[12)] 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 production of charm, colour or quarks (presumably with small x characteristic of the "sea"). 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 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[14)] 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 (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 $\bar{\nu}N$ has the same rate, $(\mu^+\mu^+)_{\bar{\nu}}$ 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 a totally different dissociation mechanism 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.

5. Deep inelastic nucleon dissociation into quarks and quark decays as a source of leptons: Consider the following mechanism:

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

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

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

but NO $(\mu^+\mu^+)$'s in $\bar{\nu}N$, NOR 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 sea quarks or associated production of charm (or colour). We can make the statement stronger: Since

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

while we expect

$$\left[\sigma^{\bar{\nu}}(\mu^+\mu^+)/\sigma^{\nu}(\mu^-\mu^-)\right]_{\text{associated production}} \approx \frac{1 + 3\epsilon + \epsilon'}{3 + \epsilon + \epsilon'} \quad ,$$

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

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

(H) In the <u>deep inelastic</u> p-p scattering process where one tags a final state proton, we may expect (if $|q^2|$ and $M_N\nu$ are as large as in νN)

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

The last estimate (10^{-3}) is the present experimental number obtained from the rate of ($\mu^-\mu^-$) production in neutrino scattering assuming 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 $\Delta F = 0$) this source will not yeild e^+ or μ^+'s, we expect e^-/e^+, μ^-/μ^+ ratio > 1 from this mechanism.

It is provocative that for the low p_T region CHORM [5)] group report an increase of an order of magnitude in absolute lepton yields - an increase, unexplained, to our knowledge, by any known mechanism, except copious photon production. Since such a mechanism must exhibit ℓ^+, ℓ^- symmetry, it would be interesting to examine ℓ^-/ℓ^+ ratio in the CHORM region for possible hints of dissociation mechanism with its inbuilt asymmetry for ℓ^-/ℓ^+ ratio becoming important at low p_T. What is clearly needed is a theoretical study of dissociation for partially confined quarks as a function of p_T, as well as an estimate of what asymmetry in ℓ^-/ℓ^+ may be expected from conventional $\Delta B = 0$, $\Delta L = 0$ mechanisms.

(K) <u>$\nu N \to \mu^- e^+ + K$'s</u> :[12)] In our model, a new mechanism for these events involves production of <u>real</u> ($c\bar{\lambda}$) quark pair from the ($\lambda\bar{\lambda}$) pair in the sea followed by quark decays to leptons:

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

Using $\Gamma(c_y^+ \to \lambda_y^0 + e^+ + \nu_e)/\Gamma(c_y^+ \to \text{All}) \sim 10\%$ (see Table II) and a production ratio (due to sea) ∿ 10%, the expected rate of these events might be ∿ 1%. Note that such a mechanism enhances[5)] the relative probability of single and multiple K associated events, which seems to be the trend of the data.[12)]

(M) <u>Multi-leptons in eN or μN due to colour production</u>: 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 colour-quantum numbers of the <u>neutral</u> colour gluon $U^0 = (\sqrt{3}V_3 + V_8)/2$ or charged coloured particles in <u>pairs</u> (e.g., V^+V^-), i.e.

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

Leptonic branching ratio for the neutral colour gluon is rather small ($\sim 10^{-3}$). 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 [13)] 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.[16)] Note that colour-pair production should lead to a tri-muon to dimuon ratio $\approx$ 1:3, where as charm-pair production should yield $\approx$ 1:10 for the same ratio (assuming charm leptonic (e or μ) - branching ratio to be $\approx$ 10 %).

To conclude, two new mechanisms (with their characteristic signatures) have been proposed in this note, for multi-lepton production, 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 decays and nucleon dissociation into integer-charge unconfined quarks, which in their turn decay into leptons with $\Delta F = 0$. The DOGMA of confinement forbids colour gluons and quarks from showing themselves as physical particles. However seductive such a dogma may be on theoretical grounds, we feel that in the end, confinement or not, is an experimental question which can only be settled in the laboratory. Among the many testable consequences, we re-emphasise the importance of measuring like-sign dilepton rates in νN versus $\overline{\nu}N$ and rates of (e^- or μ^-) versus (e^+ or μ^+) in NN collisions.

REFERENCES AND FOOTNOTES

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

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

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

4) In model (2) with $\Delta F = 2$, $\Delta B = \Delta L$, one may, on the contrary, expect q_b^+ , $q_y^+ \to e^+, \mu^+$ + mesons and no e^-, μ^- + mesons. (Thus in Sec.5, consistently substitute $q_b^+, q_y^+ \to e^+, \mu^+, q_r \to \overline{\nu}$ instead of $q_b, q_y \to \nu$ and $q_r \to e^-, \mu^-$ as a heuristic guide to predictions of model (2), though as emphasised in the text we have not yet examined any except the basic model in any real detail.) What would be tragic is if both $\Delta F = 0$, $\Delta F = 2$ amplitudes are equally strong and contribute to quark decays, such that the ratio $\ell/\overline{\ell}$ conspires to be unity. This will be an unlikely accident.

5) L. Lederman, Proceedings of the Symposium on Lepton and Photon Interactions, Stanford, August 1975.

6) The prompt leptons arising through (ρ^0, ω^0, ϕ , J/ψ, D^+D^-, $D^0\overline{D^0}$, etc.) or direct virtual photon are all (ℓ-$\overline{\ell}$) symmetric. There are, however, other asymmetric sources involving associated production.

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

8) The effective mass of a quark inside a nucleon may be much lighter than its mass outside the nucleon (Archimedes effect), on account of partial confinement.

9) Since inclusive hadronic branching ratio of charged gluons is ~30% not all of which include three or more charged particles, the constraint $[(U^\pm \to N_{ch} \geqslant 3)/(U^\pm \to N_{ch} = 1)] < 0.3$ for the source (U) of the muon in the inclusive muon experiment (M. Cavalli-Sforza et al. Phys. Rev. Letters 36, 568 (1976)), proposed by G. Snow (Phys. Rev. Letters 36, 766 (1976)) is easily met by the quark hypothesis for the μe events (Ref.2).

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

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

12) Adding the rates of $\mu^-\mu^+$ (Ref.10) 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 $\gtrsim 2\%$. If the bulk of the $\mu^-\mu^+$ events are due to two-body leptonic decays of coloured gluons, then the leptonic p_T distribution would appear to suggest a light mass gluon - perhaps as light as 1 GeV. (Private communication from R. Phillips.)

13) J.C. Pati, Talk presented at the Northeastern University Conference on Gauge Theories and Modern Field Theory (September 1975, published by MIT Press);
D.P. Sidhu, R.N. Mohapatra and J.C. Pati, preprint 1976.

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

15) 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 quarks decay into positrons + mesons (but not positive muons + mesons), while charged red quark decay into negative muons + mesons (but not negative electrons + mesons). The accompaniment of simple kaons with positrons may be understood as being due to e^+'s being strange and muons non-strange in this model.

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

Table I[*]

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 ± 5)%	≈ 18%
$\to \mu^+\nu_\mu$	(30 ± 5)%	≈18%
$\to \pi\pi,\ 3\pi,\ 4\pi,\ 5\pi,\ K\bar{K} \cdots$	(30 ∓ 10)%	≈ 54%
$\to \pi\pi e\nu,\ K\bar{K}e\nu,\ \eta\eta e\nu$	(1 to 5)%	≈(2 to10)%
$\nrightarrow \pi e\nu\ ,\ Ke\nu\ ,\ \eta e\nu$	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)'.

[*] These decay modes apply subject to the assumption that the colour gluons are the lightest colour-octet states.

Table II

Two-body decays of yellow and blue quarks in the basic model ($\Delta F = 0$, $\Delta B = -\Delta L$)

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

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

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

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

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

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

$\tau(y,b) \sim 10^{-11}$ 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 appropriately interchange K's with π, η's in the above table.

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

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

(d) $\tau(q_{y,b})$ nearly proportional to m_q^3. Lifetime estimates include multi-meson modes, which are important.

Table III[*]

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

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)
$n^-_r \to \nu_e + V^-$ $\to e^-\bar{\nu}_e$ $\to \mu^-\bar{\nu}_\mu$ $\to$ hadrons	$n^-_r \to n^0_{y,b} + \pi^-$ (c)	$n^-_r \to e^- + \bar{\nu}_e + \nu_e$ $\to e^- + \pi^0$ $\to \mu^- + K^0$	$n^-_r \to n^0_{y,b} + \pi^-$ (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) $\to p^0_r + \pi^-$ (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.	$\tau(q^-_r) \approx (10^{-11} - 10^{-12}\,\text{sec})(m_W/m_V)^4$ (d) $\tau(q^0_r) \sim 10^{-11} - 10^{-12}$ sec.	$\tau_r \lesssim 10^{-11} - 10^{-13}$ sec. depending upon $m_r - m_{y,b}$

*) 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. Only two-body semi-leptonic decay modes are listed in the table, whereas the lifetime estimates of course include multi-meson emission.

(a) Normal non-leptonic weak decays;

(b) Perhaps dominant;

(c) $\Delta B = 0$ decays due to $V^- - W^-$ mixing;

(d) For an extended symmetry (such as SU(4) × SU(4) × SU(4)' × SU(4)'), this large factor $(m_W/m_V)^4$ is absent and other decay modes are available. Inclusion of Higgs meson contributions (which we have ignored) can also somewhat alter the decay pattern and lifetime depending upon their masses.

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