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INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS

INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

DESIGN OF FUTURE EXPERIMENTS:

I - TO DISTINGUISH BETWEEN THE ALTERNATIVES OF PHYSICAL AND HIDDEN COLOUR

II - TO TEST IF THE NEUTRAL GAUGE BOSON LIES IN THE VICINITY OF PETRA-PEP REGION

(A note for experimental colleagues)

Jogesh C. Pati

and

Abdus Salam

1977 MIRAMARE-TRIESTE

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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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ADDENDUM

September 1977

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A D D E N D U M

1. Addendum p.24

If we consider the extended symmetry $SU_A(4) \times SU_B(4) \times SU'_A(4) \times SU'_B(4)$ model for quark decays, the most important consequence is that a direct mixing of the X^0's is now permitted with the new weak gauge bosons W_{14} contained in the flavour $SU_A(4)$ or $SU_B(4)$ ($W_{14} = 0$ in the basic model with flavour gauging $SU_L(2) \times SU_R(2)$). This leads to direct diagrams of the type of Fig.1 for red quarks as well, giving the following new decays (of strength $\frac{f^2}{m_X^2} \ln \frac{m_X^2}{m_{41}^2}$):

$$p_R^0 \to \nu_\mu + \text{mesons} \quad ,$$

$$n_R^- \to \nu_\mu + \text{mesons}\ (\rho^-, A_1^-, \pi^-) \quad ,$$

$$\lambda_R^- \to F^- + \nu_e \quad ,$$

$$C_R^0 \to \nu_e + \text{mesons} \quad .$$

One consequence of this is that one would observe:

$$e^- + e^+ \to (e^- \text{ or } \mu^-) + (\rho^+ \text{ or } A_1^+ \text{ etc.}) + \text{missing neutrinos}$$

originating from

$$e^- + e^+ \to n^-_{red} + n^+_{red}$$

$$n^-_{red} \to V^- + \nu \qquad n^+_{red} \to \bar{\nu}_\mu + (\rho^+ \text{ or } A_1^+ \cdots)$$

$$V^- \to e^- + \bar{\nu}_e$$

The relative frequency of these events compared with pure (μe) events would depend on the ratio $\ln(m_X^2/m_{W_{41}}^2)/\ln(m_X^2/m_{W_L^\pm}^2)$. The new mixing - $X^0 W_{41}$ - does not alter the patterns of decay modes of yellow and blue quarks, and in particular it never induces any decay modes involving charged leptons - the allowed pattern being $q_{red} \to$ neutrino + mesons.

2. Add to Ref.4:

H. Fritzsch and P. Minkowski, Nucl. Phys. B103, 61 (1976);
R.N. Mohapatra and D.P. Sidhu, Phys. Rev. Letters 38, 667 (1977), and BNL Preprint 22561;
A. De Rújula, H. Georgi and S.L. Glashow, Harvard Preprint, 1977.

3. Ref.19, now issued as ICTP, Trieste, Preprint IC/77/88.

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(A note for experimental colleagues) *

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* These notes are a compilation of earlier relevant work with some elaboration. The manuscript was completed in January 1977 except for discussion of data on new e^-e^+ and $\mu^-\mu^+$ resonances announced in June-July 1977.

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I. INTRODUCTION

A vast effort is currently going into design of experiments at the forthcoming facilities at PETRA and PEP, as well as into the design of new accelerators. The immediate goals are search for charm, for possible new flavours, for heavy leptons and eventually for $W^\pm$ and Z^0 particles. In this note, we wish to argue for the inclusion in this list of a search for unconfined integer-charge quarks and their manifest colour. We present a number of distinct signatures - at least as distinct in our opinion as signatures for new flavours (like charm) - for the detection of quarks and other coloured objects. We realize that there is a strong theoretical prejudice against manifest colour - the common assumption being that it is inexorably confined. Just for this reason, we would expect, experimental physicists will wish to mount a special effort to decide for or against the intriguing and perfectly viable alternative of unconfined colour, which we present in this note.

A second intriguing possibility recently emphasised concerns the question whether there is one relatively light neutral gauge boson (Z_0) or two (N_1, N_2) and whether the mass of one of these (m_{N_1}) is less than the mass of the charged weak vector boson $(m_{N_1} < m_{W_L^\pm})$. These questions, brought to light by the recent null or near null result on atomic parity violation [1], are relevant to testing if nature prefers a basic symmetry between left versus right - a concept which was proposed together with the hypothesis that quarks and leptons belong to one common multiplet a few years ago [2),3)]. PETRA and PEP are in an ideal position to answer these questions through the observation of asymmetries in $e^+ + e^- \to \mu^+ + \mu^-$ or $e^+ + e^- \to \pi^\pm + X$. We present in the last section the results of a recent calculation [4] for these asymmetry parameters at PETRA and PEP energies as a function of the parity-violation parameter for atomic bismuth, as they arise within the left-right symmetric theory [2].

II. THE TWO ALTERNATIVE SOLUTIONS FOR QUARK CHARGES

Recall that within a unified gauge theory of quarks and leptons [2),3)], there are two allowed solutions for quark charges.

(a) Fractional charges: For this case, the assumption of confinement is almost obligatory on the grounds that the experimental searches for (stable) fractionally charged objects are rather exhaustive; furthermore, within a unified theory, fractionally charged quarks must be associated with an octet of massless neutral colour gluons. No such massless gluon has been seen in the weak decays of π's , K's and hyperons. F1)

(b) Integer charges: There is no need here for the hypothesis of confinement. This is because within a unified theory of quarks and leptons, baryon and lepton numbers are naturally violated so that integer-charge quarks become unstable against rapid decays into leptons. Such short-lived quarks ($\tau \lesssim 10^{-11}$ to 10^{-13} sec.) are not excluded experimentally even for relatively low-mass physical quarks ($m_q \lesssim 2$ GeV).

At present there does not exist any truly satisfactory theory of quark confinement using spin-1 gluons. But even if such a spin-1 confining theory did exist, the final arbitration between fractional or integer-charges must be made by experiment. In this note, we spell out the signatures of observable quarks and physical colour (i.e. colour gluons and coloured composites) and their expected production cross-sections. As regards quark decay, we first list such general features as may be expected within the generalized quark-lepton unification hypothesis and then give the detailed predictions of one specific model (the basic model [3]) for such a unification.

Before addressing ourselves to quark decays, we consider the production and decays of coloured gluons in e^-e^+ annihilation, as well as in photoproduction in various energy ranges and in particular in the PEP and PETRA ranges. This is because the decays of these gluons are highly relevant to decay modes of quarks.

F1) Recently observations of fractionally charged objects have been reported by La Rue, Fairbank and Hebard (Ref.5)

No doubt such an observation would need further substantiation. We wish to note that (within a unified theory), observation of such fractionally charged objects without a simultaneous observation of massless gluons, would connote a discovery of prequarks rather than that of quarks, with quarks themselves being integer-charged. (Pati, Rajpoot and Salam [6]).

III. PRODUCTION AND DECAY PROPERTIES OF THE FOUR NEUTRAL COLOUR GLUONS ($\tilde{U}$, $\tilde{V}$, V^0_{K*}, $\bar{V}^0_{K*}$)

The estimates of partial widths and branching ratios given below for the decay modes of the colour-gluons are based upon the assumption that the octet of colour-gluons are the lightest colour-octet states. (Later we relax this assumption.) These estimates should apply without substantial alteration (except perhaps those for e^-e^+ and $\mu^-\mu^+$ modes) for the corresponding members of the spin-1 $q\bar{q}$ colour-octet composites, if they happen to be the lowest-lying colour-octet states instead.

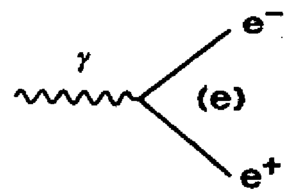
3.1 Decay modes of the colour-gauge partner of the photon (The $\tilde{U}$ gluon)

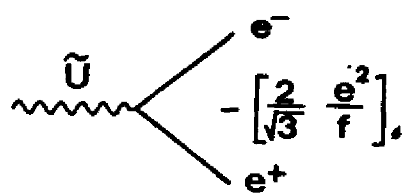
Among the octet of colour-gluons, the orthogonal colour-gauge partner of the photon (the $\tilde{U}$ gluon) occupies a special place, since it can be produced singly by e^-e^+ annihilation. If W^0_{flav} and U^0_{col} are the fields which appear in a gauge Lagrangian, the composition of the physical photon-$\tilde{U}$-complex is given by F2)

$$A = \frac{f\, W^0_{flav} + g\, U^0_{col}}{\sqrt{f^2 + g^2}} ,$$

$$\tilde{U} = \frac{f\, U^0_{col} \;\; g\, W^0_{flav}}{\sqrt{f^2 + g^2}} .$$

In terms of the canonical components V_3 and V_8, $U^0_{col} = (\sqrt{3}\, V_8 + V_8)/2$. Here g and f are the effective weak and strong gauge-coupling parameters respectively ($(g^2/f^2) < 1/10$). Thus $\tilde{U}$ is directly coupled to e^-e^+ and $\mu^-\mu^+$ through its W^0_{flav} component. Diagramatically,





F2) See Ref.3 for details.

In general $\tilde{U}$ can also mix with the second neutral gluon within the gluon-octet $V^0_{col} \equiv \frac{\sqrt{3}\,V_8 - V_3}{2}$, the eigenstates in this case would be

$$\tilde{\mathbb{U}} = \tilde{U}\cos\xi - V^0\sin\xi$$
$$\tilde{V} = \tilde{U}\sin\xi + V^0\cos\xi \quad .$$

The canonical field V^0_{col} is <u>decoupled</u> from photon and thus from e^-e^+ or $\mu^-\mu^+$. The fields $\tilde{\mathbb{U}}$ and $\tilde{V}$, therefore, couple to charged lepton pairs as well as to (hadrons + γ) only through U^0_{col} and therefore through $\tilde{U}$, the corresponding amplitudes being proportional to $\cos\xi$ and $\sin\xi$, respectively. <u>Thus there could be two gluon states instead of one coupled to e^-e^+</u> .

The amplitudes[F3)] for the various decay modes of $\tilde{\mathbb{U}}$ and $\tilde{V}$ are listed below. (More detailed discussions are given in Refs.[7] and [8] .)

$(\tilde{\mathbb{U}},\tilde{V}) \to e^-e^+$ or $\mu^-\mu^+$	$-\frac{2}{\sqrt{3}}\left(\frac{e^2}{f}\right)(\cos\xi,\sin\xi)$
$\to \eta'\gamma,\ \pi\pi\gamma,\ K\bar{K}\gamma$	$\mathcal{O}(e)\quad(\cos\xi,\sin\xi)$
$\to 2\pi,\ 4\pi,\ K\bar{K}$	$\mathcal{O}(\alpha) + \mathcal{O}(H'(\underset{\sim}{8},\underset{\sim}{8})$
$\to 3\pi,\ 5\pi,\ \rho\pi,\ K\bar{K}$	$\mathcal{O}(\alpha) + \mathcal{O}(H'(\underset{\sim}{1},\underset{\sim}{8}))$.

H' denotes the non-electromagnetic colour-symmetry breaking term [F4)], which in the simplest case may be represented by mass splittings between red, yellow and blue quarks transforming like $(\underset{\sim}{1},\underset{\sim}{8})$ under $SU(3) \times SU(3)'$, such a term would lead only to odd G-parity final states. In general, H' may contain a $(\underset{\sim}{8},\underset{\sim}{8})$ piece as well, which would contribute to decay modes involving even G-parity final states.

F3) Strictly speaking (with <u>no</u> $\tilde{U}$-V^0 mixing), the $(\tilde{U}\,e^-e^+)$ coupling is given by $-\frac{2}{\sqrt{3}}\left(\frac{e^2}{f}\right)\left(1 - \frac{\delta m_U^2}{m_U^2}\right)$ where δm_U^2 is the finite mass renormalization. Simple estimates suggest[8)] $(\delta m_U^2/m_U^2) << 1$. However, if this is a gross under-estimate $\tilde{U} \to e^-e^+$ partial width may correspondingly be lower. In this case photoproduction amplitude would be correspondingly enhanced (see Ref.[8]). A further modification of $\tilde{U} \to e^-e^+$ partial width can come about if there exist spin-1 $q\bar{q}$ colour-octet composites near the gluon states, with which the gluons can mix strongly. This important possibility will be discussed further.

F4) In order that the colour is still a good classification symmetry, we expect that H' is of order $(1 \sim 10)\alpha$. We have used this in our estimates of the partial widths.

We give below the <u>estimated</u> partial widths [9)] for some of the typical $\tilde{U}$-decay modes for the cases of the "<u>light</u>" gluon ($m_U \sim 1$ to 2 GeV) and the "<u>heavy</u>" gluon ($m_U \sim 8$ to 10 GeV) assuming $\cos^2\xi \approx 1$. The details are given in the Appendix.

It should be borne in mind that these estimates <u>for the hadronic and (hadron + photonic) partial widths</u>, dependent as they are on dynamical considerations, should be used as a good guide only for the expected order of magnitude of the corresponding partial widths. For the case of the "<u>intermediate-mass</u>" gluon ($m_U \approx 4$ GeV), the partial widths would lie essentially intermediate between those for the light and the heavy cases (see Appendix).

TABLE I (a)

<u>Decay modes</u>	<u>m_U = 1 - 2 GeV</u>		<u>m_U = 8 - 10 GeV</u>	
$\tilde{U} \to e^-e^+$ or $\mu^-\mu^+$	6 to 30 keV	(b)	40 to 200 keV	(b)
$\to \eta'\gamma$	40 to 1000 keV	(c)	$\frac{1}{5}$ to 10 MeV	(d)
$\to 2\pi\gamma,\ 4\pi\gamma,\ K\bar{K}\gamma,\ \cdots$	50 to 500 keV	(e)	1 to 5 MeV	(e)
$\to 3\pi,\ \rho\pi,\ 5\pi,\ K\bar{K},\ \cdots$	10 to 1000 keV	(f)	$\frac{1}{10}$ to 10 MeV	(f)
$\to 2\pi,\ 4\pi,\ K\bar{K},\ \cdots$	10 to 1000 keV	(g)	$\frac{1}{10}$ to 10 MeV	(g)

The leptonic and radiative partial widths must be multiplied by $\cos^2\xi$, likewise for $\tilde{V}$ by $\sin^2\xi$ if $\tilde{U}$ and $\tilde{V}$ mix (see page 5). Note that $\eta'\gamma$ decay mode will give rise to <u>monochromatic</u> γ rays and thus provide a unique signal for $\tilde{U}$.

(a) Plausible allowance is made for increase in inclusive partial widths such as $\sum_n \Gamma(\tilde{U} \to n\pi_i + \gamma)$ and $\sum_n \Gamma(\tilde{U} \to n\pi_i)$ with increase in mass of $\tilde{U}$.

(b) The expression for $\tilde{U} \to e^-e^+$ partial width (neglecting δm_U^2) is given by

$$\Gamma(\tilde{U} \to e^+e^-) = \frac{4}{9}\frac{\alpha^2 m_U}{(f^2/4\pi)}\cos^2\xi \approx \frac{(25\text{ keV})}{(f^2/4\pi)}(m_U/1\text{ GeV})\cos^2\xi \quad ,$$

where ξ is the $(\tilde{U}$-$\tilde{V})$ mixing angle mentioned before .
The values quoted above correspond to $\cos^2\xi = 1$, $(f^2/4\pi) \approx 1$ to 5.

(c) The variation essentially reflects a variation in phase space for m_U varying from ≈ 1.2 to 2 GeV, with the matrix element determined by dimensional estimate (see Appendix).

(d) The variation corresponds to the dynamical factor being $\sim(1\ \mathrm{GeV}/m_{col})$ or $(1\ \mathrm{GeV}/m_{col})^2$ (see Appendix).

(e) Variation partly due to variation in phase space and partly due to increase in multiplicity of channels with the dynamical factor being $\sim(1\ \mathrm{GeV}/m_{col})^2$ (see Appendix).

(f) Variation corresponds to $\mathcal{O}(H') \sim \mathcal{O}(1 \text{ to } 10\alpha)$. (See footnote F4).) We have assumed dynamical factor $\sim (1\ \mathrm{GeV}/m_{col})$.

(g) Assuming that the corresponding decay amplitudes are $\mathcal{O}(1 \text{ to } 10\alpha)$, which is the case if H' has a $(\underset{\sim}{8},\underset{\sim}{8})$ piece of the same order. In the absence of a (8,8) piece, the corresponding partial widths should be lower by one to two orders of magnitude.

We thus obtain

	$m_U \approx 1 - 2$ GeV	$m_U \approx 8 - 10$ GeV
$\Gamma(\tilde{U})_{Total}$	$\approx (\frac{1}{10}$ to 3) MeV	1 to 40 MeV
B.R.$(\tilde{U} \to e^-e^+)$	$\approx (\frac{1}{2}$ to 5) $\times 10^{-2}$ $(m_U = 1.2$ GeV)	(1 to 5) $\times 10^{-3}$.
	$\approx 10^{-2}$ $(m_U \approx 2$ GeV)	

Note that, according to the above estimates, $\tilde{U}$ is expected to be a relatively narrow object even if $\tilde{U}$ is as heavy as 10 GeV (i.e. $\Gamma(\tilde{U}) \lesssim 40$ MeV for $m_U \sim 10$ GeV). It should be stressed, however, that this particular conclusion is definitely a consequence of the special dynamical assumption that the matrix elements are increasingly damped with increasing colour-threshold (m_{col}) like $1\ \mathrm{GeV}^2/m_{col}^2$ (or $1\ \mathrm{GeV}/m_{col}$) as may be suggested by dispersion (or dimensional) arguments (see Appendix). If this particular assumption, however plausible, is false even partially (for example if the damping is softer than $1/m_{col}^2$), the radiative and hadronic partial widths would be larger by a factor $\gtrsim 10$ to 100 than the corresponding estimates listed in the above table, for the case of the heavy gluon.[F5] This would pose the dilemma that a heavy gluon $\tilde{U}$ would be broad $(\Gamma(\tilde{U}) \gtrsim 200$ to 1000 MeV) just like ordinary meson-resonances.[F6] <u>However, fortunately it will still carry the hallmark of colour in that its radiative decays would possess a significant branching ratio ($\gtrsim 30\%$), a feature which cannot easily be mimicked by ordinary meson-resonances</u>.

F5) For the light-gluon there would not be a significant increase in the partial widths (except perhaps within a factor of 5 for m_U near 2 GeV), even if we discard the dispersion damping.

In conclusion, even if a broad object is discovered in e^-e^+ annihilation in the PETRA and PEP regions, <u>it would be important to study whether it has significant radiative decay modes</u>. If it does, it should still readily be identified as the colour-gluon $\tilde{U}$. Note that $\tilde{U}$ should always show itself prominently in e^-e^+ annihilation because of its significant leptonic partial width $(\Gamma(\tilde{U} \to e^-e^+) \approx 20$ to 100 keV for $m_U \approx 10$ GeV).

3.2 Production of $\tilde{U}$

The $\tilde{U}$ particle may possibly be produced in reactions listed below:

(1) $e^-e^+ \to \tilde{U}$ (Integrated cross-section may be calculated from the leptonic partial width of $\tilde{U}$ given above.)

(2) $\gamma + N \to \tilde{U} + X$, $\tilde{U} \to e^-e^+$ or $\mu^-\mu^+$ (See estimate given below for rate of leptonic signal.)

F6) Long after the writing of this manuscript, we have recently learnt from Prof. L. Lederman (reporting the work of S.W.Herb et al. at the Budapest Conf. (July 1977). that a "resonance" has been observed in the $\mu^-\mu^+$ spectrum $(p + p \to \mu^-\mu^+ + X)$ at 9.5 GeV, the apparent width of the "resonance" being ≈ 1.1 GeV, the experimental resolution being ≈ 500 MeV and $\sigma \times$ branching ratio $(\mu^-\mu^+) \approx 3 \times 10^{-37}\ \mathrm{cm}^2$. Such an object could well be a superposition of two relatively "narrow" resonances ($\Gamma \lesssim 100$ MeV) separated by 400 to 500 MeV, which could then be identified either as the $\tilde{U}$ gluon and its counterpart $(q\bar{q})$ colour-octet object (Ref.7), or alternatively as two narrow new quark-antiquark composites (like J/ψ and ψ'). However, if the width of the resonance is genuinely large ~ 1 GeV, it would be more natural to identify the object as the gluon. Note, a leptonic branching ratio $\approx 10^{-4}$ would correspond to a production cross-section $\approx 10^{-33}\ \mathrm{cm}^2$.

(3) $\nu_\mu + N \to \nu_\mu + \tilde{U} + X$ (Neutral current) F7)

$\qquad\qquad \hookrightarrow e^-e^+ \text{ or } \mu^-\mu^+$

(4) $\nu_\mu + N \to \mu^- + \tilde{U} + V_\rho^+ + X$ (Charged currents) F7)

$\qquad\qquad V_\rho^+ \to \mu^+ + \nu_\mu$

$\qquad\qquad \tilde{U} \hookrightarrow \mu^-\mu^+$ (Four muons)

(5) $\mu^- + N \to \mu^- + \tilde{U} + X$

$\qquad\qquad \hookrightarrow \mu^-\mu^+$ (Trimuons) F7)

(6a) $p + p \to \tilde{U} + X_{col}$

$\qquad\qquad \hookrightarrow \mu^-\mu^+$ (Ref 9a)

(6b) $p + p \to (\mu^-\mu^+)_{virtual(\tilde{U}+\gamma)} + X_{col}$ (Ref 9a)

<u>An estimate of the mass of $\tilde{U}$ on the basis of existing experimental searches</u>

Two sets of experiments (photoproduction and e^-e^+ scans at SPEAR and Frascati) limit the mass regions where the observable gluon $\tilde{U}$ may lie.

F7) Leptoproduction of colour by either neutral or charged current (i.e. via processes (3),(4) and (5)) depends on (a) the gluon content of the nucleon and (b) the Archimedes <u>effective mass</u> ($\bar{\mu}$) of the gluon-partons within the nucleon (see Pati and Salam, Rajeshkharan and Roy and, in particular, Elias et al.[10]) Using the recent estimates of the gluon content ($\approx 25\%$) by Politzer et al.[11] which is about a factor of two lower than previous estimates and with $m_U \approx 1.2$-1.5 GeV and $\bar{\mu}^2 \approx 0.8$, GeV^2 (see later), we expect net (colour/flavour)-production above colour-threshold to be around $(2 \sim 3)\%$. This is a factor of 3-4 lower than the earlier estimates where the gluon-content of the nucleon was taken to be $\approx 50\%$ and also m_U was taken to lie typically in the 4 GeV region (see for example the estimate of neutral-current-excitation of colour by Mohapatra, Pati and Sidhu[12]). For expected dimuon signal from colour-production by neutrinos, see discussions later.

(a) <u>Photoproduction</u>

Photoproduction of $\tilde{U}$ is strongly suppressed 8) compared with that of ρ^0. This is because the colour-octet part of the electromagnetic current is essentially the source of $\tilde{U}$ (except for the small mass renormalization term), so that

$$\langle 0|J_\mu^{em}|\tilde{U}\rangle = \langle 0|J_\mu^{\tilde{U}} - (e/f)\ \delta m_U^2\ \tilde{U}_\mu|\tilde{U}\rangle = -(e/f)\ \delta m_U^2\ \epsilon_\mu .$$

Using once-subtracted dispersion relation for the gluon self-energy function $\pi(s')$ and familiar light-cone expansion analysis for the evaluation of $\mathrm{Im}\pi(s')$, one obtains (retaining only $q\bar{q}$ states)

$$\delta m_U^2 \approx (1 \text{ to } 4)\ (f^2/48\pi^2)\ m_U^2 ,$$

where the large value corresponds to the larger $m_U \gtrsim 3$ GeV. Using this value for δm_U^2 and the leptonic branching ratio of $\tilde{U}$ as listed above, one obtains 8)

$$\frac{\sigma(\gamma N \to \tilde{U} + X \to e^-e^+ + X)}{\sigma(\gamma N \to \rho^0 + X \to e^-e^+ + X)} \approx 10^{-2}\ (\tfrac{1}{5} \text{ to } 10)\ (m_U \approx 1.5 \text{ GeV})$$

$$\approx 10^{-2}\ (\tfrac{1}{2} \text{ to } 10)\ (m_U > 2 \text{ GeV}) .$$

A narrow gluon $\tilde{U}$ in the mass range 1.1 to 1.8 GeV leading to photoproduction of e^-e^+ pairs about two orders of magnitude lower than that due to ρ^0 is compatible F8) with the present photoproduction data. However, a modest

F8) A Frascati group working at DESY has found a possible narrow resonance at 1.1 GeV in photoproduction with a width less than the resolution $\sim$30 MeV. The detection was by interference with the Bethe-Heitler background in $\gamma N \to e^-e^+X$. (Report by the Frascati group at the Tbilisi Conf. July 1976). On the other hand, a Novosibirsk group has found no evidence for the production of any new resonance in $e^-e^+ \to \pi^+\pi^-X$ in the region 0.74 GeV $\leq E_{CM} \leq$ 1.34 GeV. With the <u>assumption</u> that the branching ratio into pionic modes is comparable to that of the ϕ meson, they conclude that the leptonic partial width of such a meson is less than 200 eV. Thus the situation remains unresolved and further experimental study particularly involving measurement of total cross-section in this energy range (1.0 to 1.5 GeV) is needed. New narrow resonances in the energy range (1.4-2.1) GeV have recently been reported by Frascati groups studying e^-e^+ annihilation (see discussion later).

improvement in the photoproduction search in this mass range can deny or establish the existence of a light gluon $\tilde{U}$. The photoproduction data does, however, seem to rule out a gluon in the 1.8 to 3 GeV region accepting the theoretical estimate for $\tilde{U}$ photoproduction given above.

(b) e^-e^+ annihilation

The most direct search for $\tilde{U}$, of course, involves a scan for a narrow resonance in e^-e^+ annihilation. Such a scanning search especially involving e^-e^+ total cross-section (or $e^-e^+ \to e^-e^+$, or $e^-e^+ \to \mu^-\mu^+$) had not yet been undertaken until very recently in the mass range 1.1 to 1.8 GeV. This has recently partially been carried out by three independent groups (the $\gamma\gamma$ group, the baryon-antibaryon group and the MEA group) working at Frascati in the 1.45 to 2.1 GeV region. They have discovered F9) three resonances lying at 1498 ± 2 MeV, 1820 MeV and 2100 MeV of which the one at 1498 MeV is particularly narrow (Γ = 1 to 3 MeV).

The Frascati 1498 MeV resonance: This appears to be a tentalising candidate for one of the two gluons ($\tilde{U}$ or $\tilde{V}$), which can be produced by e^-e^+ annihilation, especially in view of the fact that a radially excited ρ, ω or ϕ-like object with a mass $\approx$1.5 GeV would *a priori* be expected to have a rather large width $\gtrsim$30 MeV. Between $\tilde{U}$ and $\tilde{V}$, if the leptonic partial width of the 1498 MeV particle turns out to be rather low ($\Gamma_{e^+e^-} \approx$ .06 to .1 keV) as indicated on the basis of preliminary studies, one should perhaps identify this particle with the $\tilde{V}^0$ gluon with a mixing angle $|\sin\xi| \sim \frac{1}{5}$ to $\frac{1}{10}$ (see Sec.III.1). In this case one would expect that this 1498 MeV particle should decay primarily via the hadronic decay modes (see Table I), its leptonic and simultaneously radiative decay modes being damped by $\sin^2\xi$. More important, we would expect that the $\tilde{U}$ gluon must lie within 100 to 200 MeV of the $\tilde{V}$ gluon mass with a leptonic partial width one to two orders of magnitude bigger than that of the 1500 MeV object. We therefore especially urge that a scanning search for the $\tilde{U}$ gluon be made at Frascati in the 1300 to 1450 MeV region, which has not yet been explored & equally important decay modes of the 1498 MeV object (as also radiative branching ratios of the 1820 MeV object) be ascertained.

F9) This was reported by Dr. Capon at the European Physical Society Conference at Budapest, Hungary, 8 July 1977. We thank Drs. R. Baldini, B. Stella, A. Negro, R. Del Fabro and F. Constantini for kind communication of their results.

Below we give a summary of the present experimental status of $\tilde{U}$ in the various mass ranges assuming that it is a narrow resonance (i.e. $\Gamma(\tilde{U}) < 10$ MeV) with $\Gamma(\tilde{U} \to e^+e^-) \gtrsim 1$ keV.

Table II

Mass of $\tilde{U}$	Allowed	Excluded	Reasons
< 1 GeV	-	✓	(g-2)-muon; photoproduction and lifetime estimates
1.1-1.8 GeV	✓	-	Possible candidates at 1.1 and for $\tilde{V}$ at 1.5 GeV
1.8-3 GeV	-	✓	Photoproduction e^-e^+-search at Frascati, $\mu^-\mu^+$ production by NN.
3 - 7.6 GeV	-	(see comments below)	SPEAR search

Comment to Table II

SPEAR searches appear to exclude a narrow gluon $\tilde{U}$ ($\Gamma \lesssim 10$ MeV) with $\Gamma(\tilde{U} \to e^+e^-) \gtrsim 1$ keV in the 3.2-7.6 GeV region. However, one may not conclude from this that coloured mesons do not necessarily lie in the SPEAR region. This is because of the following circumstance.

Assume that there exists a $q\bar{q}$-colour composite (with the same quantum numbers as the gauge gluon $\tilde{U}$) but lighter than $\tilde{U}$. Assume that this composite has a narrow leptonic partial width ($\lesssim \frac{1}{5}$ keV) - on account of mixing with $\tilde{U}$ - while the $\tilde{U}$, lying higher, has the larger leptonic width ($\gtrsim$ few keV).

Now the present SPEAR search would not identify the lower-lying $q\bar{q}$ coloured composite, since its leptonic width is too small. The search may also miss the higher-lying coloured gluon, since its total width is likely to be large ($\Gamma \gtrsim 40$ MeV) on account of its envitable hadronic decays into the lower-lying $q\bar{q}$ composite mentioned above. With such a broad width it would not qualify as a narrow resonance and these are only ones for which SPEAR have measured leptonic widths.

Having said this, we should remark that leptoproduction data nevertheless appear to disfavour this possibility of medium-heavy gluon ($m_U \approx 4$ to 6 GeV, before mixing) with colour-threshold also lying near 4 GeV. This is because, allowing for the gauge factor "m_U^4"$/(q^2 -$ "m_U^2"$)^2$ for lepto-

production of colour, one obtains (Ref. 10) $F_2^{col}(x) \to \frac{1}{3}\, x\, V(x) \left(\frac{"m_U"}{\mu}\right)^4$.
Here "m_U" denotes the gluon-propagator mass (at q^2) and μ is the effective mass of the gluon-parton inside the nucleon ($\mu \ll M_N$ for consistency). Thus <u>if the gluon-propagator mass (at q^2) is not very different from the physical mass of the gluon</u>, i.e. if "m_U" $\gtrsim$ 4 GeV, then the factor("m_U"$/\mu)^4 \gtrsim 300$. This would imply an excessive rise in structure functions due to colour production, incompatible with the data. This suggests that unless the gluon-propagator mass (at q^2) is somehow drastically reduced compared with its physical value [F10], the combination of a medium heavy gluon (mass $\approx$ 4 to 6 GeV) and medium heavy (or low) colour-threshold < 5 GeV is not favoured by the leptoproduction data.

In summary, combining Table I with the comments given above, there appear to be two regions where the lightest colour-octet mesons may lie (for simplicity we assume this to be the gauge gluons).

(I) <u>Light gluon ($m_V \simeq$ 1.1-1.8 GeV)</u>

For this case, the colour-octet ($q\bar{q}$) composite mesons should lie in the 2 to 3 GeV region upwards. These would generally be broad objects since they may decay strongly into a light gluon plus mesons or a pair of gluons (masses permitting). In general the physical states may be mixtures of the canonical gluons and the $q\bar{q}$ colour-octet composites. Within this hypothesis some of the broad structures observed in e^-e^+ annihilation in the 4 to 5 GeV region may have their origin in colour. For this case, it also makes sense to assume that physical quark-masses are relatively light (the (p,n,λ) quarks having a mass perhaps as light as 2 to 3 GeV with the charm quarks being heavier by about 1.5 to 2 GeV). These quarks can be the source of the (μe) events observed at SPEAR and Doris instead of heavy leptons (see discussions later).

(II) <u>Heavy gluon ($m_V \approx$ 8 to 10 GeV)</u>: together with the assumption that not just the gluons but the entire colour spectrum symbolized by ($q\bar{q}$) colour-octet composite masses is rather high ($\approx$ 8 to 10 GeV). Correspondingly we would expect in this case that the quarks are also rather heavy ($m_q \approx$ 4 to 6 GeV).

F10) This could happen in a complete theory which incorporates the Archimedes effect properly, but here we take the conservative point of view and do not consider this possibility.

The third possibility (subject to leptoproduction reservations mentioned above) of colour threshold lying in the SPEAR region (4 GeV)upwards). The major remark here is that a relatively large leptonic partial width is not the hallmark of colour on account of the possibility of mixings among colour states.

The first case, involving light mass gluons and relatively low mass physical colour, leads to the exciting possibility that <u>all</u> the new phenomena (represented by the existence of J/ψ particles, the value of $R \approx 5$, the di-muon phenomena as well as SPEAR μe events) can be attributed to the excitation of charm plus physical colour (including quarks) with no need to postulate excitation of any further flavours or of heavy leptons on experimental grounds. In the discussions below, we shall enumerate distinguishing tests for colour in this picture.

The second possibility, involving high colour-threshold and quark-masses, is logically permissible. For this case, the Archimedes effect must be operative to an extent much more so than for the case of light physical quarks and physical gluons so as to render the effective masses of quarks and gluons inside the nucleon $\lesssim$ 300 MeV. This is not out of the question in a spontaneously broken gauge theory where masses are controlled by expectation values of Higgs particles. These expectation values can be strongly environment dependent, leading to a strong Archimedes effect.

It is worth emphasising that if quarks and gluons are moderately heavy ($m_q \sim$ 4 to 5 GeV and $m_V \sim$ 8 to 10 GeV), these should be the objects of major interest in the PETRA and PEP regions as well as for the future CERN-FNAL and Isabelle accelerators. We return to these later.

3.3 Decay modes of the other neutral gluons

(i) The $V^0 = \frac{1}{2}(V_3 - \sqrt{3}\,V_8)$, as mentioned before, can in general mix with $\tilde{U}$ (see Sec. III.1). Thus $\tilde{V}$ (= $V^0 \cos\xi + \tilde{U}\sin\xi$) can in general have the same decay modes and similar partial widths as for $\tilde{U}$. In the absence of $\tilde{U}$-V^0-mixing, the V^0 would still decay to 3π, $\rho\pi$, 5π, etc. via non-electromagnetic colour-symmetry-breaking term $H'(1,\underset{\sim}{8})$ and to 2π, 4π, etc. via $H'(\underset{\sim}{8},\underset{\sim}{8})$.

(ii) The remaining two neutral gluons V^0_{K*} and $\bar{V}^0_{K*}$ decay primarily by first converting to a virtual U^0 through a loop diagram involving charged colour-gluon W^+-mixings, followed by $U^0 \to \pi\pi\gamma$, 3π, $\rho\pi$, etc.

$$V^0_{K*} \to \pi\pi\gamma,\ \eta'\gamma,\ 3\pi,\ \rho\pi,\ldots$$

The lifetimes of V^0_{K*} and $\bar{V}^0_{K*}$ depend upon the mass difference between V^0_{K*} and U^0 as well as upon the factor ($\sin\alpha\cos\alpha$), where α denotes the mixing angle between V^+_ρ and W^+. Assuming $\sin\alpha\cos\alpha \approx \frac{1}{2}$, we obtain

$$\tau(V^0_{K*}) << 10^{-15}\ \text{sec}$$

for

$$|m(V^0_{K*}) - m(U^0)| << m_U \quad .$$

IV. PRODUCTION AND DECAY PROPERTIES OF THE FOUR CHARGED COLOUR GLUONS $(V^\pm_\rho, V^\pm_{K*})$

4.1 Decay modes

These particles decay (assuming that they are the lightest charged colour-octet objects) only because of their mixing with the charged weak-gauge bosons $W^\pm$. Hence their decay modes and corresponding branching ratios are essentially the same as for the virtual $W^\pm$ having the effective mass of the gluon. These are listed below.

Table III [(a)]

Decay modes	$m_V \approx$ 1-2 GeV	$m_V \approx$ 8-10 GeV
$(V^+_\rho, V^+_{K*}) \to e^+\nu_e$	(30 ± 5)%	≈ 12%
$\to \mu^+\nu_\mu$	(30 ± 5)%	≈ 12%
$\to 2\pi, 3\pi, K\bar{K}, \ldots$	(30 ∓ 10)%	≈ 36%
$\to DK, F\phi, F\psi, \ldots$	0	≈ 36%
$\to \pi\pi e\nu, K\bar{K}e\nu, \eta\eta e\nu$	(1 to 5)%	≈ (2 to 10)%
$\pi e\nu, Ke\nu, \eta e\nu$	Forbidden [(b)]	Forbidden [(b)] .

(a) In making the above estimates, we have used light-cone or parton-model analysis for p,n,λ quarks for $m_V > 3$ GeV (and including charm-quark when $m_V > 6$ GeV). For a lighter gluon ($m_V \sim 1$ to 2 GeV), we expect the ratio of hadronic ($\pi\pi$, 3π, 4π, $K\bar{K}$, etc.) to electronic branching ratio to be smaller than the asymptotic value 3 on account of limited phase space, which restricts hadronic channels.

(b) $\pi e\nu$ and $Ke\nu$ modes are forbidden by I-spin and strangeness-conservations, while $\eta e\nu$ mode is forbidden by SU(3) and SU(3)'. Note the distinction from charm, for which semileptonic decay modes involving single kaon emission are allowed and frequent.

The lifetimes of V^+_ρ and V^+_{K*} depend, respectively, upon the V^+_ρ-W^+ and V^+_{K*}-W^+-mixing angles, which are found to be in the ratio of $\sin\alpha$: $\cos\alpha$. For $\sin\alpha \approx \cos\alpha \approx 1/\sqrt{2}$, we obtain:

$$\tau(V^+_\rho) \approx \tau(V^+_{K*}) \approx \frac{1}{2} \times 10^{-13}\ \text{sec}\left(\frac{m_V}{1\ \text{GeV}}\right)^{-5} \quad .$$

Note that if $\sin\alpha$ is very different from $\cos\alpha$, then one member of the (V^+_ρ, V^+_{K*})-set would be longer-lived compared with the lifetime estimates given above. If gluons are light ($m_V \sim$ 1-2 GeV), it is quite possible that such gluons produced in pairs in hadronic collisions (see discussions later) would show themselves in bubble chamber as well as emulsion experiments currently being designed to detect charm particles (D,F,...) and with lifetimes **similar** to (D,F,...). Recall however the crucial distinction betwen colour and charm. For colour, semileptonic decay modes involve emission of π and K only in pairs; for charm, single K emission (i.e. D → Keν , etc.) is allowed and frequent.

4.2 Production of charged gluons

Process	Comments
(1) $p+p \to V_\rho^+ + V_\rho^- + X$ $\to V_\rho^\pm + X_{col}^\mp + X$ $V_\rho^\pm \to \mu\nu$, $\to e\nu$; $X_{col}^\mp \to$ (μ or e)	(Expect $\sigma_{V\pm X^\mp_{col}} \sim 10^{-29} - 10^{-31}$ at Fermilab and ISR-energies for $m_V \sim 1$ to 2 GeV. (This is ONE SOURCE OF PROMPT LEPTONS - if colour-threshold is low - Case I.)
(2) $e^-e^+ \to V^+_{\rho,K^*} + V^-_{\rho,K^*}$ $V^+ \to \mu\nu$, $V^- \to e\nu$	$(R_{V\bar{V}} = \frac{1}{8})$ (A partial source of μe **EVENTS**, if gluons are light; in this case red quarks would be a more dominant source - see later).
(3) $\nu_\mu + N \to \mu^- + V_\rho^+ + X$ $V_\rho^+ \to \mu^+ + \nu_\mu$ $\to \mu^- + X^+_{col} + X$ $X^+_{col} \to \mu^+\nu + \ldots$ (dimuons)	$(d\sigma_{col}/\, d\sigma_{flav})$ depends on the glue-content of the nucleon and the effective gluon-parton-mass $\bar{\mu}$ (see footnote F7)) p.9 and references therein). With a recent estimate of the glue-content being nearly $\approx 25\%$ and with $m_U \approx 1.2$-1.5 GeV and $\bar{\mu}^2 \approx .8$ GeV^2, one expects $(d\sigma_{col}/d\sigma_{flav}) \approx 2 \sim 3\%$ and thus a dimuon rate from colour production $\approx (\frac{1}{3}$ to $\frac{1}{2})\%$ (inclusive colour-muonic branching ratio ≈ 15 to 20%).
(4) $\mu^- + N \to \mu^- + V_\rho^+ + V_\rho^- + X$ $V_\rho^+ \to \mu^+\nu$, $V_\rho^- \to \mu^-\bar{\nu}$	(TRIMUONS) .

V. PRODUCTION AND DECAY OF QUARKS

5.1 General picture for quark decays

By convention, we assign

Baryon number (B) = 1 for quarks
= 0 for leptons

Lepton number (L) = 0 for quarks
= 1 for leptons $(\nu_e, e^-, \mu^-, \nu_\mu)$.

We also define

$$\text{Fermion number } F \equiv B + L \quad .$$

In a unified theory of quarks and leptons, baryon and lepton numbers as well as the fermion number[F11)] can, in general, be violated, with the spontaneous breakdown of the unified quark-lepton symmetry. If quarks are integer-charged this would render them unstable against decay into leptons and anti-leptons. In general, the following set of decay modes would arise:

$$\left.\begin{array}{l} q \to \ell + \ell + \bar{\ell} \\ \quad \to \ell + \text{mesons} \end{array}\right\} \quad \Delta F = 0 \ (\Delta B = -\Delta L = \pm 1)$$

$$\left.\begin{array}{l} \quad \to \bar{\ell} + \ell + \bar{\ell} \\ \quad \to \bar{\ell} + \text{mesons} \end{array}\right\} \quad |\Delta F| = 2 \ \ (\Delta B = \Delta L = \pm 1)$$

and also

$$q \to \bar{q} + \text{mesons} \quad \longrightarrow \quad |\Delta F| = 2 \ \ (\Delta B = 2,\ \Delta L = 0)$$

Depending upon the details of the unification hypothesis and the nature of spontaneous symmetry breaking, there would of course be selection rules, which could lead to one set of decay modes predominating over the others. These selection rules can also vary from quark to quark depending upon its flavour and colour. This is exemplified below in detail for example for the basic model. (We refer to the gauge model of Ref. 3 , based on the "effective" symmetry $SU(2)_L \times SU(2)_R \times SU(4)'_{L+R}$ operating in the space of the familiar sixteen-plet of fermions, as the basic model.)

An intriguing intermediate state for some of the transitions mentioned above is provided by a diquark state.[F12)] If diquarks exist and are lighter than quarks, a quark may convert to a diquark plus a virtual antiquark via strong interactions followed by the antiquark converting to an antilepton ($\Delta F = 0$) or to a lepton ($|\Delta F| = 2$),

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F11) This would especially be true if the gauge symmetry were as big as SU(8) × SU(8). Alternatively, a supersymmetric treatment of the unified gauge symmetry, with the inevitability of supersymmetric multiplets containing F = 2 scalar particles (necessary for parity-conservation of strong inter-actions) makes $\Delta F = 2$ transitions a distinct possibility.

F12) Some of the features involving decays of diquark states have in-dependently been noticed by A. Schorr[13)].

$$q \xrightarrow{\text{strong}} \phi_{qq} + \text{"}\bar{q}\text{"}_{\text{virtual}}$$
$$\hookrightarrow \bar{\ell} + \text{mesons}\ (\Delta F = 0)$$
$$\hookrightarrow \ell + \text{mesons}\ (\Delta F = 2)\ .$$

In its turn, the diquark (assumed heavier than the normal baryons (N,Λ,Σ,Ξ)) could decay as follows:

$$\phi_{qq} \xrightarrow{\text{strong}} B(qqq) + \text{"}\bar{q}\text{"}_{\text{virtual}}$$
$$\hookrightarrow \bar{\ell} + \text{mesons}\ (\Delta F = 0)$$
$$\hookrightarrow \ell + \text{mesons}\ (\Delta F = 2)\ .$$

Thus, even for a theory for which $\Delta F = 0$ dominates over $\Delta F = 2$ (e.g. for the basic model the diquark-intermediate step[F13] may lead to more anti-leptons being observed in quark decays than leptons. This possibility was not considered in our earlier papers.[3),14),15)]

<u>Baryon number conserving decays</u>: Apart from the baryon number violating decays exhibited above, there should of course exist (masses and quantum numbers permitting) baryon number conserving non-leptonic as well as leptonic decays of some quarks arising simply from normal weak interactions. This would in general involve colour-conserving as well as colour-changing transitions (the latter arising from weak W^+-V^+-mixings). As examples one may have:

$$\lambda^0_{\text{yel,blue}} \to p^+_{\text{yel,blue}} + \pi^- \ ; \ n^0_{\text{yel,blue}} + \pi^0 \ ,$$
$$c^+_{\text{yel,blue}} \to \lambda^0_{\text{yel,blue}} + \pi^+ \ ,$$
$$p^0_{\text{red}} \to n^0_{\text{yel,blue}} + \gamma \ ,$$
$$c_{\text{red,yel,blue}} \to \lambda_{\text{red,yel,blue}} + e^+ + \nu_e \ .$$

F13) The existence of diquark with decay modes as exhibited above brings in the new feature that final states involving (diquark + quark) production would have a lower leptonic/non-leptonic branching ratio compared with those involving coloured baryons or $q\bar{q}$ coloured mesons.

5.2 <u>Quark decays[15)] in the basic model ($\Delta F = 0$)</u>

There are two special features pertaining to baryon and lepton-number violations in a class of gauge models exemplified by the basic model.

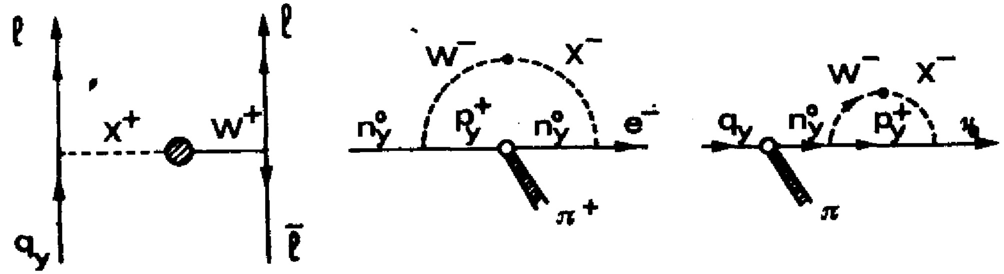
(a) Baryon and lepton-number violations are brought about in this class of models as follows. The gauge particles $X^{\pm}$ as well as $X'^{\pm}$, which, respectively, couple the yellow and blue quarks of a given flavour to the lepton of the same flavour, get mixed (due to spontaneous symmetry breaking) with the charged quark gauge particles $W^{\pm}$. This violates B and L, but not F. In turn, this induces decays of yellow and blue quarks into leptons, strictly satisfying the rule:

$$\Delta F = 0 \ ; \ \Delta B = -\Delta L = \pm 1 \qquad \text{(basic model)}\ .$$

(b) The gauging pattern[F14)] of the basic model is such that the neutral gauge particle X^0, which couplesthe red quarks to the lepton, cannot mix with the neutral flavour-gauge particle W_3. As a result, for this class of models, <u>the decays of the red quarks differ characteristically from those of the yellow and blue quarks</u>.

<u>Decays of yellow and blue quarks in the basic model</u>

There are three basic mechanisms for the decay of the yellow and blue quarks in the basic model; these are depicted by Fig.1(a), (b) and (c), respectively.



(a) (b) (c)

<u>Fig.1</u>

F14) This feature is relaxed in the extended gauge model $[SU(4)]^4$, in which X^0 mixes with W_{14}, see J. Pati and A. Salam[16)].

The types of decay modes which can be induced by these figures differ characteristically from each other. While Fig.1(a) and Fig.1(b) can lead to emission of charged leptons (Fig.1(a) would in fact lead to emission of two charged leptons for decays of neutral yellow and blue quarks, e.g. $n^0_{yel,blue} \to e^- + e^+ + \nu_e$) ; Fig.1(c) has the unique feature (stemming from electric charge and fermion-number conservation) that it cannot lead to emission of charged leptons; it can lead to emission of neutrinos only. (This is because $Q(\nu_e) = Q(n^0_y)$; but $Q(e^-) \neq Q(p^+_y)$.)

Comparing Figs.1(a), 1(b) and 1(c), we see that Fig.1(a) is damped by two large mass denominators $(1/m^2_X)$ and $(1/m^2_W)$; so also is Fig.1(b), assuming that the emission of the composite pion from the quark-line is associated with a form factor[F15] $(F_{qq\pi}(q^2) \sim 1/(q^2-m^2))$. Fig. 1(c), on the other hand, is damped by only one large mass denominator $(1/m^2_X)$. Taking this into account, one sees that Fig.1(c) provides by far the dominant mechanism for the decay of the yellow and blue quarks:

$$\Gamma(\text{Fig.1(c)}) \gg \Gamma(\text{Fig.1(b)}) \quad ,$$
$$\Gamma(\text{Fig.1(c)}) \gg \Gamma(\text{Fig.1(a)})$$

This, in turn, has the profound consequence that insofar as the baryon-number violating decays are concerned, the yellow and blue quarks may decay only into (neutrinos + mesons), but not to charged leptons. Below we list these decay modes in more detail.

F15) Note that the presence of such a form factor does not play any significant role for Fig.1(c)), since the relevant momentum transfer is small.

Table IV

Decays of yellow and blue quarks in the basic model

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

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

$$\lambda^0_{yel,blue} \to \nu_e + \bar{K}^0 \quad ; \quad \nu_\mu + \eta \quad ,$$
$$\to p^+_{y,b} + \pi^- \quad ; \quad n^0_{y,b} + \pi^0 \text{ (normal weak decay)} \quad ,$$

$$c^+_{yel,blue} \to \nu_e + D^+ \quad ; \quad \nu_\mu + F^+ \quad , \text{(a)}$$
$$\left.\begin{array}{l} \to \lambda^0_{y,b} + \pi^+ \quad ; \quad p^+_{y,b} + \pi^0 \\ \to \lambda^0_{y,b} + e^+ + \nu_e \quad . \end{array}\right\} \text{(normal weak decay)}$$

(a) Masses permitting. These modes may be partially suppressed relative to the other modes if D and F are not much lighter than the charmed quark.

Consistent with the constraints of the basic model, we estimate:

$$\tau(q_{yel,blue}) \sim 10^{-11} \text{ to } 10^{-12} \text{ sec } (m_q \sim 2 \text{ to } 3 \text{ GeV}) ,$$
$$\sim 10^{-12} \text{ to } 10^{-13} \text{ sec } (m_q \sim 4 \text{ to } 5 \text{ GeV}) ,$$

the lifetime being roughly proportional to m_q^{-3}. The lifetime estimate includes multimeson emission, which is important (average meson multiplicity ≈ 3 to 4 for light quark: $m_q \approx 2$ to 3 GeV).

Decays of red quarks in the basic model

Here there are four distinct cases depending upon the relative masses of quarks versus gluons and of red quarks versus yellow and blue.

Case 1: $m_q > m_V \quad ; \quad 0 < m_r - m_{y,b} < m_\pi$,

Case 2: $m_q > m_V \quad ; \quad m_r - m_{y,b} > m_\pi$,

Case 3: $m_q < m_V \quad ; \quad 0 < m_r - m_{y,b} < m_\pi$,

Case 4: $m_q < m_V \quad ; \quad m_r - m_{y,b} > m_\pi$.

The decay modes and lifetimes for these four cases are listed below.

Table V †)*)

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

Case 1	Case 2	Case 3	Case 4
$m_q > m_V$ $0 < m_r - m_{y,b} < m_\pi$	$m_q > m_V$ $m_r - m_{y,b} > m_\pi$	$m_q < m_V$ $0 < m_r - m_{y,b} < m_\pi$	$m_q < m_V$ $m_r - m_{y,b} > m_\pi$
$p_r^0 \to \nu + V^- + \pi^+$ $\to n_{y,b}^0 + \gamma$	$p_r^0 \to n_{y,b}^0 + \pi^0$ (c)	$p_r^0 \to n_{y,b}^0 + \gamma$	$p_r^0 \to n_{y,b}^0 + \pi^0$ (c)
$n_r^- \to \nu_e + V^-$ $\to e^-\bar{\nu}_e$ $\to \mu^-\bar{\nu}_\mu$ $\to$ hadrons	$n_r^- \to n_{y,b}^0 + \pi^-$ (c)	$n_r^- \to e^- + \bar{\nu}_e + \nu_e$ (d) $\to e^- + \pi^0$ (d) $\to \mu^- + K^0$ (d)	$n_r^- \to n_{y,b}^0 + \pi^-$ (c)
$\lambda_r^- \to \nu_\mu + V^-$ $\to p_r^0 + \pi^-$ (a) $\to n_r^- + \pi^0$ (a)	same as on left	$\lambda_r^- \to p_r^0 + \pi^-$ (b) $\to n_r^- + \pi^0$ (b)	same as on left
$c_r^0 \to \lambda_r^- + \pi^+$ (a) $\to p_r^0 + \pi^-$ (a) $\to \lambda_{y,b}^0 + \gamma$ (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) $\tau(q_r^0) \sim 10^{-11} - 10^{-12}$ sec.	$\tau_r \lesssim 10^{-11} - 10^{-13}$ sec. depending upon $m_r - m_{y,b}$

(cont'd)

Table V (cont.)

†) Notation: $m_{r,y,b}$ denote masses of red, yellow and blue quarks. $V^\pm$ stands for the charged gluons $V_\rho^\pm$ or $V_{K*}^\pm$. The lifetime estimates assume quark mass ≈ 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 (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 following closely the dynamical restrictions of the basic gauge model.

5.3 Production of quarks

	Comments
(1) $e^-e^+ \to q_i + \bar{q}_i$	$(R(q_i\bar{q}_i) = R(q_i)_{flavour} = (Q_i^{flavour})^2$. If quarks and gluons are light, can attribute SPEAR μe events and jets to $q\bar{q}$ pair production followed by q and $\bar{q}$ decays (see later for distinguishing tests from heavy leptons).
(2) $p + p \to q_i + \bar{q}_i + X$ $\bar{p} + p \to q + \bar{q} + X$	Expect[F16] $\sigma_{q\bar{q}} \sim 10^{-30}$ to 10^{-32} cm^2 for $m_q \sim 2$ to 3 GeV at Fermilab and ISR energies. For heavier quarks $m_q \gtrsim 4 \sim 5$ GeV, expect production cross-section to be still more severely suppressed.
(3) $\underbrace{p + p}_{B=6} \to \underbrace{(q + q + q)}_{B=3} + \underset{(B=3)}{X}$	Dissociationrate hard to predict. But eventually (perhaps at the new accelerators planned at CERN, FNAL and Isabelle) dissociation should become important enough to be noticeable. One hallmark of dissociation is that it will lead to $e^-/e^+ \neq 1$ [F17] (charge asymmetry). If like dimuons in neutrino physics are partly due to dissociation, then the latter may be more frequent in deep inelastic collision, i.e. $p + p \to p + X$ where one tags the final state proton.
(4) $\nu_\mu + N \to \mu^- + q + \bar{q} + X$ $\quad q \to \mu^-,\ \bar{q} \to \mu^+$	
$\to \mu^- + q_{red} + q_y + q_b + X$ $\quad q_{red} \to \mu^-,\ q_y \to \nu,\ q_b \to \nu$	(NUCLEON dissociation) (like DIMUONS)
(5) $\mu + N \to \mu + q + \bar{q} + X$	

F16) Rates for $q\bar{q}$ production and nucleon dissociation into three quarks in high-energy hadronic collisions are difficult to predict on dynamical grounds. They depend upon the barrier transmission coefficient corresponding to partial confinement represented by the difference between masses of free physical quarks and constituent quarks inside the nucleon. Judging from rates of $D\bar{D}$ or J/ψ production, one may make an educated guess that $\sigma_{q\bar{q}} \sim 10^{-30}$ to 10^{-32} cm^2 for $m_q \sim 2$ to 3 GeV at Fermilab and ISR energies.

F17) If dissociation is found to occur predominantly at high p_T , it would be easy to distinguish the associated (e^-/e^+) asymmetry from the charm originated (e^-/e^+) asymmetry.

Remark

Decaying integer-charge quarks and heavy leptons can mimick each other in many respects, especially if they are produced via the virtual photon as in e^-e^+ annihilation, where their production cross-sections would be similar (see remarks later about quark versus heavy lepton interpretation of the SPEAR (μe) events). However, when production cross-sections in hadron-initiated processes are concerned, there is the important distinction that neutral heavy leptons are produced through weak interactions only, which may easily be distinguished from the more copious quark production possibly $\approx 10^{-30}$–10^{-32} cm^2 (for $m_q \approx 2$ to 3 GeV). Also important is the distinction that relatively slow quarks (with lifetime $\sim 10^{-11}$ to 10^{-13} sec) should scatter against nuclei with cross-sections $\sim 10^{-27}$ cm^2 , something unattainable for heavy leptons.

VI. INTERPRETATIONS OF THE NEW PHENOMENA UNDER THE HYPOTHESIS OF LIGHT PHYSICAL COLOUR ($m_V \approx$ 1-1.8 GeV, $m_{p,n,\lambda} \sim 2$ to 3 GeV)

1. J/ψ (3.1) and ψ' (3.7) and structures in 4-5 GeV region

$$\left.\begin{array}{lll} J/\psi\ (3.1) & (c\bar{c}) & (n = 1,\ {}^3S_1) \\ \psi'\ (3.7) & (c\bar{c}) & (n = 2,\ {}^3S_1) \end{array}\right\} \text{(same as standard interpretations)} .$$

Some of the structures in the 4-5 GeV region could be attributed to colour-octet states (made out of p,n,λ quarks) as well as (or alternatively) to $(n = 1, {}^3S_1)$ $(c\bar{c})$ colour-octet state. These states would be relatively broad ($\Gamma \sim 20$ to 100 GeV) since they can decay strongly into lower-lying gluons plus mesons.

2. $R = R_{flavour} + R_{colour}$

$$= \sum_{quarks} (Q_i^{flav})^2 + \frac{1}{8} \left(\frac{m_U^2}{\mu^2}\right)^2 ,$$

where m_U denotes gluon propagator mass (at q^2) and μ the effective mass of the gluon partons. With $(m_U^2/\mu^2) \sim 3$ to 4, a value suggested from the analysis of eN and μN scattering and $R_{flavour}$ = (10/3 + log corrections); we get $R \approx 3.7 + (1$ to $2) \approx 4.7$ to 5.7

consistent with the present value of R . Thus, in this case, there is no need to postulate heavy lepton or new flavour excitation (apart from charm) to account for the observed value of R .

3. $e^-e^+ \rightarrow \mu e$ + missing momentum

If (p,n,λ) quarks have a physical mass ≈ 1.8 to 2 GeV and if gluons are lighter than quarks [F18] with $m_r - m_{y,b} < m_\pi$ (Case I) - a perfectly feasible possibility - then one can attribute the μe events to pair production and decays of charged red quarks (see Table V - Case 1):

$$\begin{array}{ccccl} e^-e^+ \rightarrow q^-_{red} & + & q^+_{red} & & \\ \downarrow & & \downarrow & & \\ V^-+\nu & & V^++\bar{\nu} & & \\ \hookrightarrow e^-+\bar{\nu}_e & & \hookrightarrow \mu^++\nu_\mu & & \text{(Two-step three-body decay)} . \end{array}$$

The momentum spectrum of the (μe) pairs thus arising via a two-step process, though distinct from a pure two-body or three-body spectrum, is consistent [17] with the observed momentum spectrum particularly with gluons being as light as 1.5 GeV. An accurate determination of the momentum spectrum in the 200 to 500 MeV/c region can help distinguish between quark versus heavy lepton origin of the events.

From $R(n^-_r n^+_r) + R(\lambda^-_r \lambda^+_r) = \frac{2}{9}$ and the gluon leptonic branching ratio we obtain

$$R_{q\bar{q}}(\mu^+e^-) = R_{q\bar{q}}(\mu^-e^+) \approx 1.6 \text{ to } 2.5\% \quad ,$$

F18) It should be stressed that the constraint $m_q > m_V$ permitting the interpretation of the μe events in terms of quark decays is a constraint that arises within the basic model. It is conceivable that this constraint may be relaxed in a more general framework; but it is not clear whether one may still be able to preserve all the desirable features of the basic model, i.e. suppression of semileptonic events and charge ±2 as well as four charged lepton events (see later), except possibly in models where quarks are not point-like but are composites of preons.

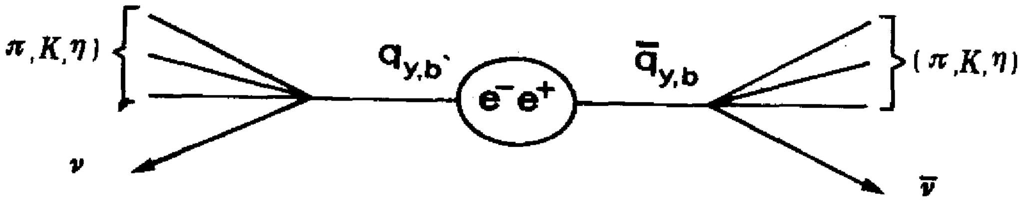
compatible with the data. Once again there is no need to postulate heavy leptons to account for the μe events once we allow for physical quark excitation. (We list later distinguishing tests [F19] between the quark and the heavy lepton interpretations.)

4. $e^-e^+ \rightarrow$ hadronic jets

While charged red quarks decay into charged leptons, we saw, at least in the basic model, that the remaining ten quarks (whose pair production contributes a value [F20] (10/3) - (2/9) = 28/9 to R) decay in the end to neutrinos + mesons (π,K,η) These $q\bar{q}$ pairs at higher energies would give rise to the final state hadrons (mesons) emerging in the form of two jets opposite to each other with a distinction characteristic of spin-$\frac{1}{2}$ parentage. This provides a novel and simple explanation of the jet structure observed experimentally. It should be stressed that there would still exist a piece in R (e.g. from the gluonic contribution $\frac{1}{8}\,(m^2_U/\mu^2)$ and also from the fact that quark form factor at SPEAR energies may be close but not identical to unity), which would reflect itself in direct production of hadrons through $q\bar{q}$ and gluon-anti-gluon recombination (this piece is similar to the mechanism of hadron production in the confined quark picture). Such a piece could lead to an increase in average pion multiplicity $\langle n_\pi \rangle$ with increasing energy as observed experimentally.

F19) Within the basic model (Ref. 3) with the pattern of spontaneous symmetry-breaking exhibited in Ref. 3, W_L's mix with X's, as a result one deduces that the decay of charged red quarks to leptons via the (gluon + ν) intermediate step would exhibit an effective V+A interaction (see Ref. 17). This, however, is not a characteristic feature of the quark hypothesis for the μe events. The model via its left-right symmetry permits a complete interchange of the left versus right vacuum expectation values ($\langle B \rangle \leftrightarrow \langle C \rangle$, see Ref 3). This would mix X's with W_R's (instead of W_L's), in which case red quark decays into leptons (via $q^-_r \rightarrow V^- + \nu \rightarrow \mu^- + \bar{\nu}_\mu + \nu$) would be governed by an effective V-A interaction (rather than V+A).

F20) Recall that in the colour-gauge theory (Refs. 2 and 3) only the colour-singlet part of electromagnetic charge of quarks contributes to R (see Ref. 10). Thus integer-charge quark-partons contribute the same amount to R as fractionally-charged quark-partons within the colour-gauge theory.



One immediate **test** of this particular explanation of the jet structure is that there must exist MISSING ENERGY and MISSING MOMENTUM associated with the hadronic events corresponding to the energy and momentum carried away by the neutrinos.

VII. DISTINCTION BETWEEN LOW-MASS PHYSICAL COLOUR AND HIDDEN COLOUR PICTURES FOR THE NEW PHENOMENA

We have shown above that the new phenomena in the present accelerator energy range can simply be attributed to the hypothesis that colour is physical (quarks are integer-charged) with relatively low threshold (i.e. $m_q \sim 2$ GeV and $m_V \sim 1.1 \sim 1.8$ GeV and [F21] $m_{colour} \sim 2$ to 4 GeV) and that charm as well as colour (including quarks) has been excited. This obviates the need for postulating either heavy lepton or heavy quark flavour excitation (apart from charm), contrary to the case of hidden colour (fractionally charged quarks), where the hypotheses of heavy lepton excitations appear to be necessary to give an overall explanation to the new phenomena.

F21) m_{colour} denotes the mass of colour continuum which symbolizes the mass scale for onset of scaling for colour-structure functions. It presumably should correspond to the masses of $(q\bar{q})$ colour-octet states (or resonances).

Below we list a set of tests, which should help clearly distinguish between the two alternatives: low mass gauge physical colour versus confined colour.

Phenomena	Low mass gauge physical colour	Confined colour
1) $\left(\frac{\sigma_L}{\sigma_T}\right) \xrightarrow{\text{Asymp}} f(x) \neq 0$	Yes	No
2) Two-step, three-body decay spectrum for the μe events: $e^-e^+ \to \mu e + X$, which can be distinguished from genuine three-body decay by a measurement of the lepton momentum spectrum in the region of 200-500 MeV.	Yes $e^-e^+ \to q^-_{red} + q^+_{red}$ $q^-_{red} \to V^- + \nu$ $\quad \hookrightarrow e^- + \nu_e$ $q^+_{red} \to V^+ + \nu$ $\quad \hookrightarrow \mu^+ + \nu_\mu$ (see text)	No Heavy lepton decaying to charged leptons ($L^- \to \mu + \nu + \bar{\nu}$) would give rise to genuine three-body decay spectrum
3) Observation of high-momentum (μe) signals accompanied by pair of pions, $e^-e^+ \to \mu e + \pi^+ + \pi^- + \ldots$	Yes Expected rate for such semileptonic signal ~ 2 to 5% compared with leptonic (μe) events	No Heavy lepton origin of the μe events cannot give rise to semileptonic signals
4) Missing energy and momentum carried away by neutrinos in the hadronic jets produced by e^-e^+ collision	Yes Such missing energy and momentum must exist for the quark interpretation of the μe events (see text)	No No simple explanation would arise for such missing energy and momentum with confined quark
5) Observation of mono-energetic photons in e^-e^+ collision in the vicinity of threshold for μe production	Yes $e^-e^+ \to p^0_{red} + \bar{p}^0_{red}$ $p^0_{red} \to n^0_{yel} + \gamma$ $\quad \hookrightarrow \nu$ + mesons (see text)	Not expected

Phenomena	Low mass gauge physical colour	Confied colour
6) Observation of short-lived charged particles ($\tau \sim 10^{-13}$ to 10^{-15} sec), whose semileptonic decay modes always involve a pair of pions, a pair of kaons but never a single π or K	Yes A clear signal for charged gluons $V_\rho^\pm \to \mu^\pm + \nu + \pi^+ + \pi^-$ $\not\to \pi + \mu + \nu$ (see text for branching ratio)	No All flavour objects (like charm particles) will have semi-leptonic decay modes involving single K or π
7) Observation of narrow states ($\Gamma \sim \frac{1}{5}$ to 5 MeV) in the Frascati, Novosibirsk and Orsay region ($E_{cm}(e^-e^+) \approx$ 1.1-1.8 GeV) with at least one of them having a significant radiative decay branching ratio and leptonic partial width $\gtrsim$ 1 keV	Yes clear signal for the neutral gluons ($\tilde{U}, \tilde{V}$)	No
8) Observation of particles in emulsion-bubble chamber studies with lifetimes $\sim 10^{-12}$ - 10^{-13} sec, which decay either into (mesons + missing neutrinos), or into (charged leptons + missing neutrinos) like a heavy lepton, but which can scatter relatively strongly against nuclei ($\sigma \sim$ mb)	Yes Clear signal for decaying integer-charge quarks $q^+_{yel,blue} \to \nu + (\pi, K, \ldots)$ $q^-_{red} \to V^- + \nu$ $\hookrightarrow e^- + \bar{\nu}_e$	No

As pointed out before, a crucial feature of low-mass physical colour, in addition to the tests mentioned above, is that the lightest colour-octet vector mesons (whether these are gluons or $q\bar{q}$ colour-octet mesons) must lie in the 1.1 to 1.8 GeV region. This is required on the basis of existing experimental searches. The same mass region for the gluons is also required so far as the simple basic model is concerned for a consistent interpretation of the SPEAR μe events in terms of pair production and decays of quarks. (If gluons are not light, SPEAR events may still be quark decays, but the simple basic model will not be available and a more elaborate version of our theory will be needed.) We therefore cannot overemphasise the importance of a search for the light gluon in this low-mass region. Such a search, especially via a scan in e^-e^+ annihilation (at Frascati, Novosibirsk and Orsay) and photoproduction should be given priority so that it may clearly eliminate or establish this intriguing hypothesis of low-mass physical colour.

VIII. HIGH-MASS PHYSICAL COLOUR ($m_{colour} \sim$ 8 to 10 GeV)

The colour threshold may lie higher, for example, in the SPEAR region or, as stated before, more likely in the 8 to 10 GeV region (with quarks having their physical masses higher than 4 to 5 GeV).

From the purely experimental point of view (i.e. from the point of view of PETRA and PEP regions, for example), the existence of such narrow states (see discussions in Sec.III on expected width of high-mass $\tilde{U}$ gluon) in the 8 to 10 GeV region with relatively large leptonic partial width ($\Gamma(\tilde{U} \to e^+e^-) \sim$ 20 to 100 keV)[F22] and the existence of physical integer-charge quarks with masses in the 4 to 6 GeV region would be of considerable interest in that they would fill a possible gap between charm-particle threshold and the thresholds for the production of W and Z.

[F22] It is worth noting that such leptonic partial widths are considerably larger than the expected partial width of a $b\bar{b}$ composite, b being a "bottom" quark with charge $\frac{1}{3}$ (see review by Barnett [18]) for the expected signal for production of $b\bar{b}$ composites.

IX. CONCLUSIONS

In this note we have argued for the existence of manifest colour and integer-charged unstable quarks (decaying into leptons or antileptons). Regretfully, from within the theory we cannot give precise predictions for the physical masses of the particles concerned, which must be determined by experiment. However there are unmistakable signatures for quarks and colour, depending on the possible mass regions.

1. Colour: The unmistakable signature of one of the lowest colour state is its relative narrowness (width 1-10 MeV) and its radiative decay involving photons ($\sim$ 30%). (Unless its spin parity is 1^-, the state may not readily be produced singly in $e^+ + e^-$ collisions but may be more easily produced for example in $N\bar{N}$ collisions.) Higher colour states would strongly decay into this lowest state + normal hadrons and could be broad. Such states may also mix among themselves and also with the lowest colour state, so that e^+e^- width may not be as decisive an index for colour as the radiative decay width as mentioned above.

2. There is no contradiction with any present experimental data in assuming that the lowest colour state is the gauge gluon ($J^{PC} = 1^{--}$) and that such a gluon lies below 1.6 GeV in mass (light gluon case). Such a light gluon would be produced at Orsay, Frascati or Novosibirsk experiments and also in photoproduction experiments. If the existence of such a gluon could be confirmed unambiguously, this would provide an explanation for SPEAR (μe) events without need for heavy leptons within the context of our basic model, provided that quarks have a physical mass $\approx$ 1.9 GeV. In this respect it is important to stress that decaying quarks and decaying heavy leptons can mimic each other in almost all respects except for details like two-step versus one-step three-body decays and the rates of semi-leptonic signals (see Table on p.30).

3. If light colour gluons do not exist, colour may have manifested itself in the medium mass SPEAR region and have been difficult to identify since radiative decays of states in the 4-7 GeV region resonances have not received experimental attention yet. (This possibility has some theoretical difficulties which are mentioned in the text); or, as is more likely, colour as well as quarks are relatively more massive (colour beyond 8 GeV, quarks $\gtrsim$ 4-5 GeV). In this event, we must look to PEP and PETRA particularly for the discovery of colour. Lifetimes of colour and quark states in these

energy ranges will be $\lesssim 10^{-16}$ and 10^{-13} secs. respectively, with the signatures described in the text.

4. In the PETRA-PEP region there is a possibility of a new effect due to the exchange of exotic X mesons which convert leptons into quarks ($e^+e^- \to (q + X) + e^+ \to q + \bar{q}$). These X particles are a crucial ingredient of a truly unified quark-lepton theory. In the basic model the X's are heavy but extension of the basic model permits the X mass to be relatively light. The energy at which X effects should manifest themselves and bring about marked departures of $e^+ + e^-$ cross-sections from the expected QED-like $\frac{1}{s}$ behaviour, is $\frac{e}{f} m_X$.

5. Left-right symmetry: Its possible implications for atomic parity and high-energy e^-e^+ collision experiments: We have so far concentrated on spelling out the distinctive features of physical colour. Since this note is addressed to experimental colleagues, we wish to conclude it by drawing attention to an important redevelopment of the neutral current sector of our unified theory and its possible manifestation at PETRA and PEP, in $e^+e^- \to \mu^+\mu^-$, $\pi^+\pi^-$ and also in high-energy pp and $\bar{p}p$ machines. In our unified gauge model [3] the basic gauge structure $SU(2)_L \times SU(2)_R \times SU(4)'_{L+R}$, which contains within it the subgroup $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ relevant for weak and electromagnetic interactions, is left-right symmetric in the sense that for every left-handed (V-A) current coupled to the set of gauge particles $(W_L^\pm, W_L^3)$, there exists a parallel (V+A) current coupled to a distinct set of gauge particles $(W_R^\pm, W_R^3)$ with equal strength.

Quite naturally, the theory contains two neutral weak gauge bosons N_1 and N_2 in addition to the photon. Depending upon the pattern and parameters of spontaneous symmetry breaking, N_2 as well as the charged right-handed gauge particles $W_R^\pm$ can be very heavy ($\gtrsim$ 1000 GeV); in this case the theory would descend to the familiar $SU(2)_L \times U(1)$ theory for weak and electromagnetic interactions with only one relatively light neutral gauge particle N_1 ($\equiv Z^0$) with a mass $\approx$ 80 GeV. There is the allowed and intriguing alternative [3], however, that both neutral gauge particles N_1 and N_2 remain relatively light ($m_{N_1} \sim m_{N_2} \sim$ 50 to 120 GeV). For this case, Pati, Rajpoot and Salam [4] have shown in a recent note that so far as left-handed neutrino (ν_L) or right-handed antineutron ($\bar{\nu}_R$) processes are concerned, the consequences of the left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)$ theory with two light neutral gauge bosons are identical with those of the old $SU(2)_L \times U(1)$ theory, assuming that quark masses and W_L-W_R mixing may be neglected compared to W_L^+ mass. On the other hand, the left-right symmetric theory (with $m_{N_1} \sim m_{N_2}$) differs drastically in its predictions from those of the "left-handed" $SU(2)_L \times U(1)$ theory for all processes involving four-component electrons (or muons). Thus in general it differs from the $SU(2)_L \times U(1)$ theory in its predictions for

i) the atomic parity violation parameter Q_W,

ii) the rates and asymmetry parameters for $e^-e^+ \to \mu^-\mu^+$, $\pi^+\pi^-$, $\pi^\pm + X$, etc.,

iii) the rates and asymmetry parameters for dilepton production by hadrons $(pp \to \mu^+\mu^- + X)$.

If the atomic parity violation parameter Q_W for Bismuth turns out to be rather small, as suggested by recent experiments, one can use such small values of Q_W (with either sign) to make definite predictions, firstly for the masses of the two neutral gauge bosons N_1 and N_2 and, secondly for the rates and asymmetry parameters for $e^-e^+ \to \mu^-\mu^+$, etc.

So far as the masses of N_1 and N_2 are concerned, the range of predictions as a function of Q_W are indicated below:

$(Q_W/Q_W^{(0)})_{Bi}$	$m_{W_L^+}$ (GeV)	m_{N_1} (GeV)	m_{N_2} (GeV)
1	67	81	∞
0	67	67	107
-1	67	53	98

These predictions are given for $\sin^2\theta_W \approx 0.3$; $Q_W^{(0)}$ denotes the value of Q_W for the $SU(2)_L \times U(1)$ theory. Note that there is the exciting prospect that $m_{N_1} < m_{W_L^+}$ if experimentally $(Q_W/Q_W^{(0)})$ turns out to be negative. The corresponding predictions for $e^-e^+ - \mu^-\mu^+$ and $\pi^-\pi^+$ asymmetry parameters are given in Table I.

Note that as long as Q_W is either small [1] in magnitude (compared to its $SU(2) \times U(1)$ value), or opposite in sign, the left-right symmetric theory would inevitably predict that the parity conserving forward-backward asymmetry $|A^{\mu\mu}|$ must be strongly enhanced by a factor (≈ 2 to 5) compared to its $SU(2)_L \times U(1)$ value even at PETRA and PEP energies. Should experiments

show relatively large forward-background asymmetry (see Table I) or parity violating asymmetry parameters with signs opposite to those of $SU(2) \times U(1)$, they would provide clear signatures in favour of the left-right symmetric theory together with the characteristic prediction of a light N_1. We urge that a priority be given to the study of asymmetry parameters at PETRA and PEP.

Equally distinct predictions emerge for dilepton production by hadrons even at ISR energies. These will be reported in a forthcoming preprint [19].

APPENDIX

$$\Gamma(U \to e^- e^+) = (4/9)\ [\alpha^2/(f^2/4\pi)]\ m_U \approx \left(\frac{25\ \text{keV}}{f^2/4\pi}\right)\left(\frac{m_U}{1\ \text{GeV}}\right)$$

$$\Gamma(U \to \eta'\gamma) = \frac{1}{12\pi}\left(\frac{g^2_{U\eta'\gamma}}{m^2}\right)\left[\frac{m_U^2 - m'^2_\eta}{2m_U}\right]^3$$

$$\Gamma(U \to \pi\pi\gamma) \sim \frac{1}{96\pi^2}\left(\frac{g^2_{U\pi\pi\gamma}}{m^4}\right) m_U \int_0^{E_\gamma^{max}} dE_\gamma \left[1 - \frac{4m^2}{m_U^2 - 2m_U E_\gamma}\right]^{1/2} E_\gamma^3$$

$$\Gamma(U \to \pi\pi) \sim \left(\frac{g^2_{U\pi\pi}}{48\pi}\right) m_U$$

$$\Gamma(U \to \rho\pi) \sim \left(\frac{g^2_{U\rho\pi}}{(96\pi)m^2}\right)\left[\frac{m_U^2 - m_\rho^2}{m_U}\right]^3$$

In each case, the effective decay constants are defined such that they are dimensionless, the dimension of the matrix element being appropriately given by an appropriate power of a characteristic dimensional mass (m), whose value depends upon the dynamics. We take for our consideration

$$(g_{U\eta'\gamma}/m) \sim \begin{cases} \dfrac{g_{\rho\pi\gamma}}{m_U} & \text{(dimensional argument)} \\[2ex] \dfrac{g_{\rho\pi\gamma}}{m_U^2}\ (1\ \text{GeV}) & \text{(dispersion theory)} \end{cases}$$

$$\frac{g_{U\pi\pi\gamma}}{m^2} \sim \frac{e}{m_U^2} \quad \text{(dispersion and dimensional argument)}$$

$$\frac{g_{U\rho\pi}}{m} \sim \frac{g_{\omega\rho\pi}\,\mathcal{O}(H_8')}{m_U} \quad \text{(dimensional)}$$

Table I

e^-e^+ asymmetries as a function of Q_W^+

		$SU(2)_L$	$\times$ $SU(2)_R$	$\times$ $U(1)$	theory	$SU(2) \times U(1)$ limit
Q_W input		147	88	0	−49	−146
M_{N_1} (GeV)		53	58	67	73	81
M_{N_2} (GeV)		98	100	110	124	∞
$L^{\mu\mu}$	$\sqrt{s}$ = 28	3%	1.8%	0	−1%	−2.5%
	$\sqrt{s}$ = 38	3.1%	2.9%	0	−1.8%	−4.9%
$A^{\mu\mu}$	$\sqrt{s}$ = 28	−31%	−25%	−17%	−14%	−8%
	$\sqrt{s}$ = 38	−71%	−58%	−38%	−30%	−16.5%
$\rho_L^{\pi\pi}$	$\sqrt{s}$ = 28	−11%	−6%	0	+2.9%	7.9%
	$\sqrt{s}$ = 38	−37%	−18%	0	+6.7%	16%

$L^{\mu\mu}$ is the parity violating parameter (F_4/F_1) characterizing longitudinal asymmetry for $e^-e^+ \to \mu^-\mu^+$ with longitudinally polarized incident beam (Ref.20). $A^{\mu\mu}$ is the parity-conserving forward-backward asymmetry parameter $(\equiv(N_f-N_b)/(N_f+N_b))$, where N_f and N_b are the numbers of μ^+'s in the forward and backward hemispheres relative to incident e^+. The parameter $\rho_L^{\pi\pi}$ denotes the longitudinal asymmetry for $e^-e^+ \to \pi^- + \pi^+$ (Ref.21).

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