

V + A CURRENTS COUPLING OLD QUARKS TO NEW *

Y. ACHIMAN

Institut für Theoretische Physik, Universität Heidelberg

T.F. WALSH

Deutsches Elektronen-Synchrotron DESY, Hamburg

Received 10 September 1976

We study some consequences of the existence of new quark flavors. We do this in the framework of gauge models, with V + A couplings of old to new quarks and allowing for mixing of different $SU(2) \times U(1)$ representations. High-energy neutrino and e^+e^- experiments may suggest (and can prove) the existence of new flavors. Low-energy neutrino neutral current experiments are sensitive to the way new quarks and their currents are added to the standard Weinberg-Salam model. We show that if new quarks with weak couplings to old u, d quarks are needed at all, low-energy neutral current data may favor a new class of models having non-diagonal neutral currents. However, the special case of a maximal charm-changing neutral current appears to be excluded by high-energy experiments.

1. Introduction

There is now evidence that particles with a new quantum number and mainly strangeness-changing decays do exist [2]. If this is so, it supports the GIM mechanism as the correct explanation of the absence of strangeness changing neutral currents [3]. This also supports a pleasing analogy between quarks and leptons [4] which avoids anomalies in gauge theories.

This scheme does not explain why the new hadrons are so massive. The psions ($c\bar{c}$ states) are much heavier than normal mesons, though their level spacing is similar. A new mass scale of order m_ψ seems to have appeared. It is natural to speculate that yet undiscovered structure exists on this new scale. There may even be evidence in e^+e^- [5,6] and neutrino scattering [5,7,8] for new flavors beyond charm.

Large deviations from a linear energy dependence of $\sigma(\nu N)$ or $\sigma(\bar{\nu} N)$ might be explained by a large scaling violation in the standard scheme [9], or by copious production of new hadrons above a certain threshold. According to the usual view charmed hadrons cannot be produced copiously in $\nu_\mu(\bar{\nu}_\mu)N \rightarrow \mu^-(\mu^+) + \dots$ as they arise either

* This is an expanded version of ref. [1].

from diffractive fragmentation of the current (small $x = Q^2/2M$) or their production is suppressed by a factor $\sin^2 \theta_C$. Usually one also assumes scaling with a small $q\bar{q}$ "sea" component in the nucleon.

Recent experiments at FNAL do not agree with the standard Weinberg-Salam-GIM scheme expectations for $\bar{\nu}_\mu N$ scattering, even for large x [7]. Perhaps this is evidence that a new heavy quark coupled to valence u, d quarks is needed [8]. If the GIM mechanism is used to suppress strangeness changing neutral currents, the left handed $V - A$ part of the valence quarks u and d is saturated (up to small additional non-Cabibbo mixing which we shall ignore). The new currents must then be right-handed ($V + A$) [10]. This is our motivation for studying the consequences of such currents coupling old valence (u, d) quarks to new quarks. Of course new heavy quarks may exist and be almost decoupled from u and d . We shall not discuss this.

The most general *valence* part of an $SU(2) \times U(1)$ hadronic neutral current can be written

$$J_{Z^0} = \frac{1}{2} \{ L(u)(\bar{u}u)_{\text{L}} - L(d)(\bar{d}d)_{\text{L}} + R(u)(\bar{u}u)_{\text{R}} - R(d)(\bar{d}d)_{\text{R}} \\ + R(t)(\bar{t}t + \bar{t}u)_{\text{R}} + R(b)(\bar{b}b + \bar{b}u)_{\text{R}} \} - 2 \sin^2 \theta_w J_{\text{e.m.}}, \quad (1)$$

where $(\bar{q}q)_{\text{L,R}} = \bar{q} \gamma_\alpha (1 \mp \gamma_5) q$ and t, b are heavy quarks of charge $\frac{2}{3}, -\frac{1}{3}$. We have neglected repeated thresholds (see the appendix). If the GIM mechanism is used for the $V - A$ sector one has $L(u) = L(d) = 1$. If we do not allow for mixing of different representations of $SU(2) \times U(1)$ (e.g. mixing a singlet with one component of a doublet), then $R(t) = R(b) = 0$ and $R(u) = 2\tau_u, R(d) = 2\tau_d$ are integers. This case ("fancy") was considered in ref. [11].

We consider here the possibility of general mixing of $V + A$ singlets into doublets in the context of $SU(2) \times U(1)$ gauge models [12]. This means that $R^2(u), R^2(d) \leq 1$ and we aim to show that this is consistent with experiment. Models are classified in the appendix according to their contribution to deep inelastic $\nu N, \bar{\nu} N$ scattering through the valence quark couplings. We shall ignore $q\bar{q}$ in the nucleon. This is a good enough approximation, as we are mainly concerned with low energies.

The mixings we consider lead to non-diagonal neutral currents. These are observable when the mixing involves a valence quark ($R(t)$ or $R(b)$ non zero). There are then large increases of $\sigma(\nu_\mu N \rightarrow \nu_\mu + \dots)$ or (favored) $\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)$ above t or b threshold. There is no positive evidence for such flavor changing neutral currents yet.

We study the constraints on new currents arising from leptonic interactions, hadronic neutral current data at low energies and parity violating transitions in atoms. The constraints turn out to mildly disfavor models with new quarks and $V + A$ currents coupling them to u, d but *without* representation mixing. Of course, the Weinberg-Salam model persistently agrees with all published low energy neutral current data. This data alone does not imply that new quarks are needed.

For completeness we also study some high-energy properties of the new class of $V + A$ models allowed by low-energy data.

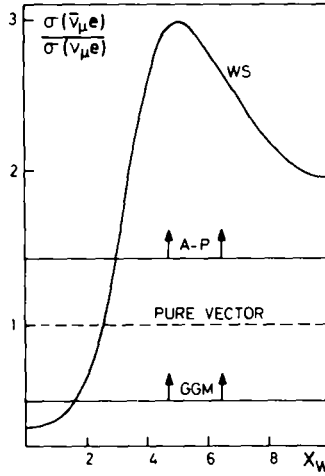


Fig. 1. Ratio of ν_{μ} to $\bar{\nu}_{\mu}$ scattering on electrons as a function of x_W .

2. Leptons

We can not disregard the lepton sector. The pure leptonic neutral currents involve the same two parameters as the hadronic [14] - i.e.

$$x_W = \sin^2 \theta_W, \quad z = \left(\frac{M_{Z^0} \cos \theta_W}{M_W} \right)^2 \quad (2)$$

Moreover the axial neutral current of the electron is important for the calculation of parity violation in heavy atoms.

Only electrons are available as lepton targets, and we presume that only left-handed neutrinos are currently manufactured. Then the leptonic cross sections are fixed by the $SU(2) \times U(1)$ representation to which e_L^- and e_R^- belong. Note that if we want to cancel anomalies [13], $V + A$ lepton couplings must be present somewhere

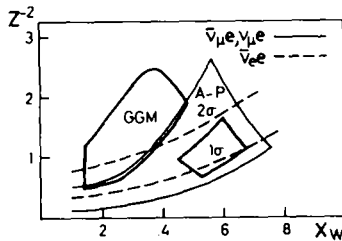


Fig. 2. Limits on z^{-2} as a function of $x_W = \sin^2 \theta_W$ for $\bar{\nu}_{\mu} e^-$, $\nu_{\mu} e^-$ and $\bar{\nu}_e e^-$ scattering, taking option (i) in the text.

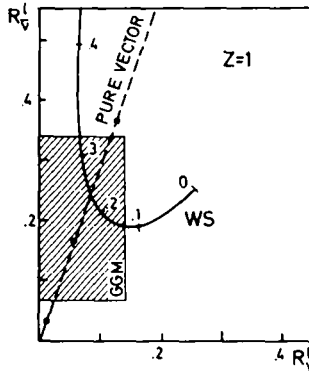


Fig. 3. The ratios $R_{\nu}^{\ell} = \sigma(\nu_{\mu}e^{-})/\sigma_{V-A}(\nu_e e^{-})$ and $R_{\bar{\nu}}^{\ell} = \sigma(\bar{\nu}_{\mu}e^{-})/\sigma_{V-A}(\bar{\nu}_e e^{-})$ for $z^{-2} = 1$ as a function of $x_w = \sin^2\theta_w$. The GGM data is shown.

(but not necessarily for e^{-}). We select two options, (i) $e_{\bar{R}}$ is a singlet – i.e. no change from WS in the leptonic sector, (ii) $e_{\bar{R}}$ is in a doublet *

$$\begin{pmatrix} N \\ e^{-} \end{pmatrix}_{\bar{R}}$$

This leads to a pure vector neutral lepton current [15].

The cross sections for ν_{μ} and $\bar{\nu}_{\mu}$ are both proportional to z^{-2} ; the ratio $\sigma(\bar{\nu}_{\mu}e^{-})/\sigma(\nu_{\mu}e^{-})$ depends only on x_w . This is shown in fig. 1, together with the Gargamelle (GGM) [16] limit and the Aachen-Padova (AP) [17] data.

In fig. 2 we use the GGM and AP data for $\bar{\nu}_{\mu}e^{-}$, $\nu_{\mu}e^{-}$ and the Irvine $\bar{\nu}_e e^{-}$ [18] data to study limits on z^{-2} as a function of x_w . Fig. 3 shows $R_{\nu}^{\ell} = \sigma(\nu_{\mu}e^{-})/\sigma_{V-A}(\nu_e e^{-})$ and $R_{\bar{\nu}}^{\ell} = \sigma(\bar{\nu}_{\mu}e^{-})/\sigma_{V-A}(\bar{\nu}_e e^{-})$ for the special case $z^{-2} = 1$.

3. Hadrons

The appendix lists some models involving V + A doublets containing valence quarks. The general charged and neutral currents take the form

$$\begin{aligned} J_w = & (ud_{\theta})_L + (\bar{c}s_{\theta})_L + \cos \alpha (\bar{u}b)_R + \eta_{\alpha} \sin \alpha (\bar{u}b')_R \\ & + \cos \beta (\bar{t}d)_R + \eta_{\beta} \sin \beta (\bar{t}d)_R + \dots, \end{aligned} \tag{3a}$$

* We ignore mixing of $e_{\bar{R}}$ with a singlet $L_{\bar{R}}$.

$$\begin{aligned}
 2J_Z = & (\bar{u}u)_L - (\bar{d}d)_L + A(\bar{u}u)_R - B(\bar{d}d)_R \\
 & + (1 - \eta_\alpha^2) \cos \alpha \sin \alpha (\bar{u}t + \bar{t}u)_R + (1 - \eta_\beta^2) \cos \beta \sin \beta (\bar{d}b + \bar{b}d)_R \\
 & - 4x_w \left(\frac{2}{3} \frac{1}{2} (\bar{u}u)_{L+R} - \frac{1}{3} \frac{1}{2} (\bar{d}d)_{L+R} \right) + \dots
 \end{aligned}
 \tag{3b}$$

We denote quarks with charge $\frac{2}{3}$ by t, t', t and those with charge $-\frac{1}{3}$ by b, b', b . Furthermore

$$\begin{aligned}
 A &= \cos^2 \alpha + \eta_\alpha^2 \sin^2 \alpha, \\
 B &= \cos^2 \beta + \eta_\beta^2 \sin^2 \beta,
 \end{aligned}$$

where $\eta_\alpha, \eta_\beta = 0$ or 1 only (see the appendix). Note that all non-valence terms in (3) have been dropped (but are needed to reproduce the full $SU(2) \times U(1)$ algebra). The quarks labelled t (or b) must sometimes be identified with c, t or t' (b, b'); if $t = c$ then charm-changing neutral currents result.

In this paper we only discuss the consequences of (3a), (3b) for inclusive scattering on isoscalar targets and for parity violating transitions in atoms [19] *.

4. Low energy

Below threshold for producing heavy quarks the ratio of neutral to charged current cross sections is

$$R_\nu^0 = \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu + \dots)}{\sigma(\nu_\mu N \rightarrow \mu^- + \dots)} = \frac{z^{-2}}{36} \{ 3[6 + A^2 + B^2] - 4[9 + 2A + B]x_w + \frac{80}{3}x_w^2 \},
 \tag{4a}$$

$$\begin{aligned}
 R_{\bar{\nu}}^0 = & \frac{\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)}{\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ + \dots)} = \frac{z^{-2}}{36} \{ 9[2 + 3A^2 + 3B^2] - 36[1 + 2A + B]x_w \\
 & + 80x_w^2 \},
 \end{aligned}
 \tag{4b}$$

where x_w and z are defined in (2). We label models by (A, B) .

Since the low-energy CERN data is below all heavy particle thresholds, we use it to restrict models. As in the leptonic case we first compare $\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)/\sigma(\nu_\mu N \rightarrow \dots)$ to restrict x . This is done in fig. 4 with the CERN Gargamelle (GGM) data

* For a restricted version of this analysis see ref. [25] where $z = 1$.

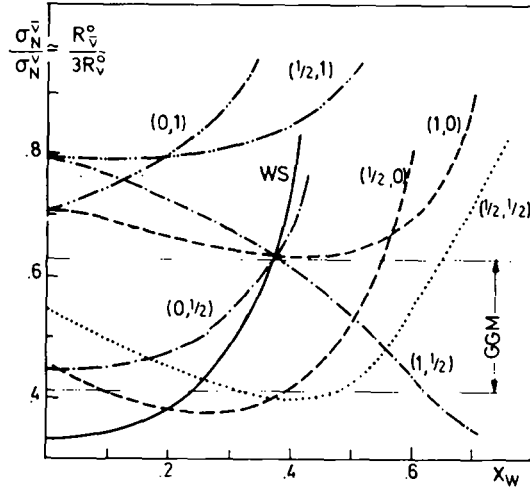


Fig. 4. The ratios of neutral current cross sections for $\bar{\nu}_\mu$ and ν_μ on an isoscalar target.

$$\frac{\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)}{\sigma(\nu_\mu N \rightarrow \nu_\mu + \dots)} \approx 0.52 \pm 11 \text{ (GGM) [16]} = \frac{R_\nu^0}{3R_\nu^0} .$$

Models with $B = 1$ appear disfavored, and models with vector neutral currents (implying $\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots) = \sigma(\nu_\mu N \rightarrow \nu_\mu + \dots)$) are excluded [20], but otherwise nearly complete freedom for (A, B) is allowed*.

Fig. 5 contains the allowed regions of x_w, z^{-2} for the models which pass the preceding check. Notice that different regions of x_w, z^{-2} are favored by models with differing (A, B) . All the models shown have allowed regions of x_w, z^{-2} which overlap the allowed area in fig. 2 for the leptonic case. Fig. 6 shows a conventional $R_\nu R_-$ plot.

Independent constraints come from parity-violating transitions in heavy atoms. The effect (a rotation of the plane of polarization of light passing through a gas) is proportional to [19]

$$z^{-1} \langle N | J_Z^V(\text{had}) | N \rangle \langle e^- | J_Z^A(\text{lept}) | e^- \rangle , \tag{5}$$

(proportional to the atomic weight $Z + N$) plus smaller terms; of course (5) vanishes for a pure vector leptonic current (e.g. in the model of Fayet [15]). Following con-

* There clearly exists a continuum of allowed models; we only exhibit a few examples with discrete (A, B) .

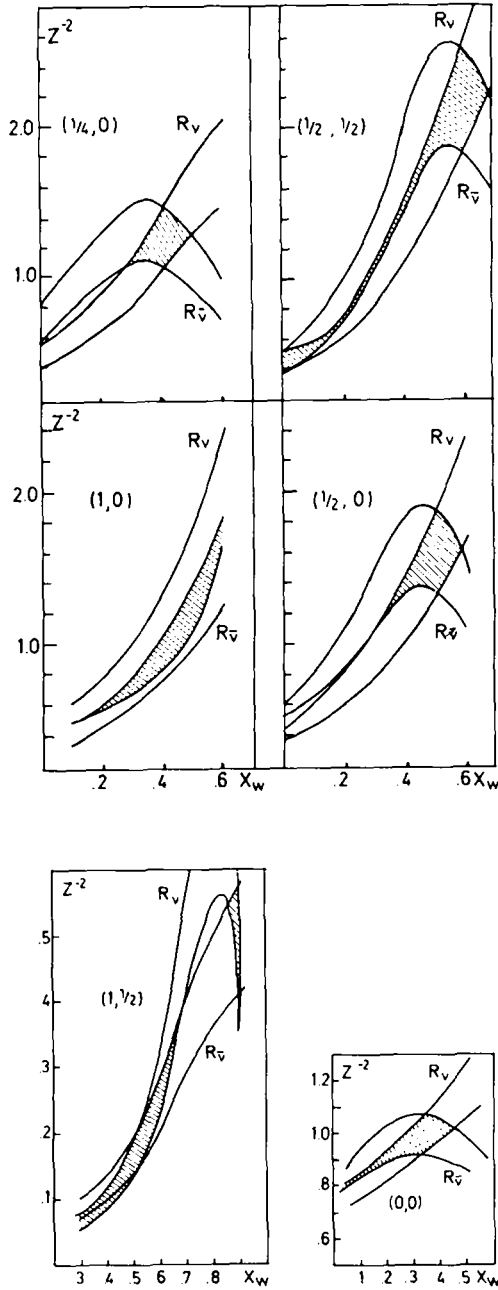


Fig. 5. The allowed regions for z^{-2} versus $x_w = \sin^2 \theta_w$ for models which pass the check on fig. 4. The GGM data was used.

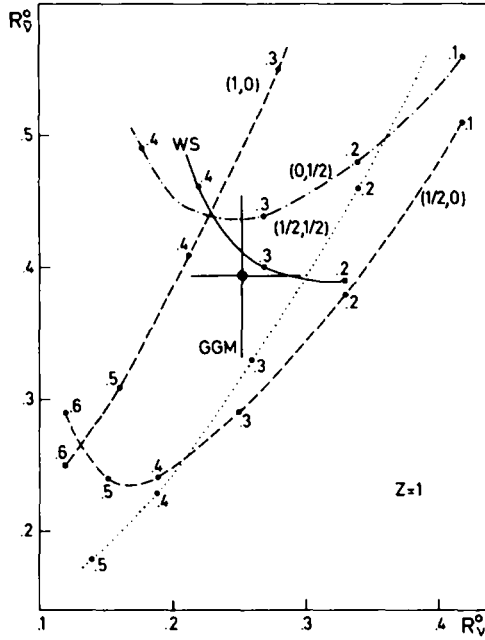


Fig. 6. Ratios of neutral to charged current cross sections for $z^{-2} = 1$ compared to GGM data.

vention we write this

$$Qz = -(4x - 1 + B - 2A)Z - (1 + 2B - A)N, \tag{6}$$

for the remaining case of interest here (lepton sector as in the WS model).

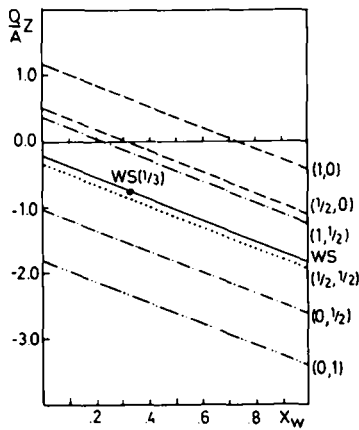


Fig. 7. The parity violating effect per nucleon for bismuth, $Qz/(Z + N)$, with Q defined as in the text.

In fig. 7 we show $Qz/(Z + N)$ as a function of x . All models give results lying between those for (1, 0) and (0, 1), while $(\frac{1}{2}, \frac{1}{2})$ is practically degenerate with the WS case (for which $z = 1$).

The atomic parity violation experiments are not yet complete, and we have only a very preliminary report [19] that the effect seen does not agree with that predicted by the (1, 0) model.

Recalling that $\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)/\sigma(\nu_\mu N \rightarrow \nu_\mu + \dots)$ disfavored the (0, 1) model, we arrive at the still very tentative conclusion that if new quarks with V + A couplings to old valence quarks are needed at all then most probably $A < 1$ or $B < 1$ or both. In our framework this implies the existence of non-diagonal (flavor-changing) neutral currents.

5. High energy

We have concentrated on low-energy data so far. If new V + A coupled favors exists there is the intriguing possibility that they are attenuated in a way which leads to flavor changing neutral currents. As such models have not yet been studied, it is interesting to ask what might happen at very high energy, above new thresholds.

We use the parton model to study this. At high energies it is an open question whether the $q\bar{q}$ sea contribution is important or not. It is also not clear how rescaling takes place above a new quark threshold (it is implicit in our discussion that Bjorken scaling holds below and very far above any new threshold). We shall confine ourselves to semiquantitative predictions assuming (i) no $q\bar{q}$ sea (valence quarks only); (ii) the scaling variable $x = -q^2/2M_p\nu$ is replaced by [8]

$$\tilde{x} = \frac{-q^2 + M_H^2}{2M_p\nu},$$

above the new threshold, where M_H is the mass of the produced heavy quark. Light quark distributions are written $q(x) \rightarrow q(\tilde{x})$. For the input electroproduction data we use Bodek's fit [21]. A similar method was successfully used by Barnett [8,22] and others [23,24] in discussing the conventional fancy quark models (these authors also discuss neutral currents).

We shall henceforth set $\cos \beta = \eta_\beta = 0$, (suggested by the absence of y anomalies in $\nu_\mu N$ scattering) and concentrate on (A, 0) models. Fig. (8) shows the prediction of these models for the ratio $\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ + \dots)/\sigma(\nu_\mu N \rightarrow \mu^- + \dots)$ [7] and for the average y for antineutrinos $\langle y \rangle^{\bar{\nu}}$ [7]. We see that a mass for the new charge $\frac{1}{3}$ quark b as low as 2.5 GeV is not excluded provided $\cos^2 \alpha < 1$. For $m_b = 4$ GeV and higher $\cos^2 \alpha \approx 1$ is acceptable, provided a $q\bar{q}$ sea contribution is present [8].

We turn now to neutral current effects above thresholds. We have already remarked that dramatic effects may appear due to flavor-changing neutral currents. The ra-

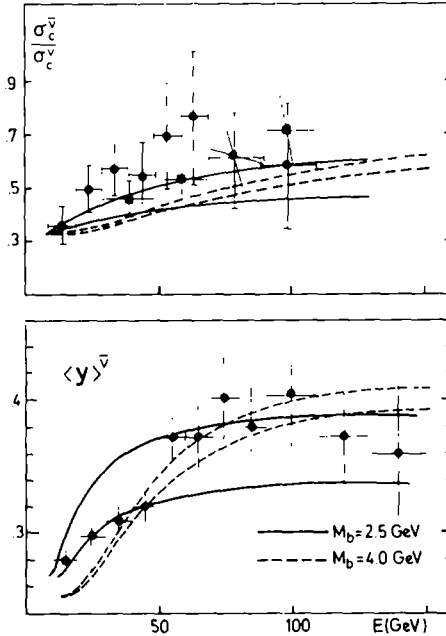


Fig. 8. HPWF: data for $\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ + \dots)/\sigma(\nu_\mu N \rightarrow \mu^- + \dots)$ and $\langle y \rangle^{\bar{\nu}}$, compared to some specific models. We set $B = \eta_\beta = 0$; for $m_b = 2.5$ GeV $\cos^2 \alpha = 0.4$ and 0.2 ; for $m_b = 4$ GeV $\cos^2 \alpha = 0.6$ and 0.5 (dashed lines). The lower lines are for the smaller $\cos^2 \alpha$.

tios of neutral to charged current cross sections have the form ($A, B \neq 1$)

$$R_\nu = \frac{R_\nu^0 + \cos^2 \alpha \sin^2 \alpha K(E/E_T) + \cos^2 \beta \sin^2 \beta K(E/E_T)}{1 + \cos^2 \beta K(E/E_T)}, \tag{5a}$$

$$R_{\bar{\nu}} = \frac{R_{\bar{\nu}}^0 + 3 \cos^2 \alpha \sin^2 \alpha \bar{K}(E/E_T) + \cos^2 \beta \sin^2 \beta \bar{K}(E/E_T)}{1 + 3 \cos^2 \alpha \bar{K}(E/E_T)}. \tag{5b}$$

Here, K and \bar{K} describe the rescaling above threshold and E_T is the threshold energy $E_T = M_T^2/2M_p$.

In order to present some representative calculations we fix $B = 0$ and $m_b = 4$ GeV as suggested by the charged current data. If there is no attenuation ($A = 1$) we expect $R_{\bar{\nu}}$ to go down. For $A < 1$ the ratio for $\bar{\nu}_\mu$ depends strongly on m_t , while that for ν_μ changes little (see fig. 9). For a charm-changing neutral current $m_t = m_c = 1.5$ GeV there is a dramatic jump in $R_{\bar{\nu}}$ above Gargamelle energies provided $\cos^2 \alpha$ is not near unity (fig. 9). This is in obvious contradiction to recent FNAL data [7]. We consider this evidence against substantial charm-changing neutral currents. Other

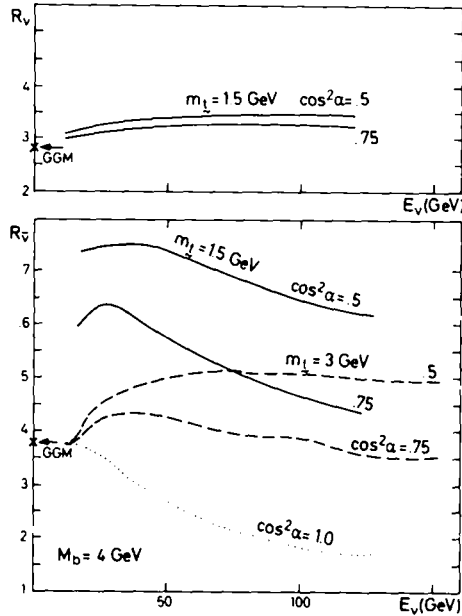


Fig. 9. The ratios of neutral to charged current cross sections for some models with flavor-changing neutral currents. We used $B = \eta_\beta = 0$ and $m_b = 4$ GeV. For ν_μ we only show the results for a charm-changing neutral current ($m_t = 1.5$ GeV). For $\bar{\nu}_\mu$ we also show predictions for $m_t = 3$ GeV (dashed lines) and purely diagonal neutral currents (dotted).

flavor changing neutral currents with higher m_t are not yet excluded. Independent information on $\bar{\nu}_\mu N \rightarrow \nu_\mu + \dots$ and $\nu_\mu N \rightarrow \nu_\mu + \dots$ is evidently needed to clearly disentangle thresholds in charged and neutral current scattering.

We conclude with some remarks on the characteristics of new thresholds in $\bar{\nu}_\mu N \rightarrow \mu^+ + \dots$ and $\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots$, $\nu_\mu N \rightarrow \nu_\mu + \dots$. If the increase of $\sigma_{cc}(\bar{\nu}_\mu)/\sigma_{cc}(\nu_\mu)$ and $\langle \gamma \rangle^{\bar{\nu}}$ seen in FNAL [7] is due to b -quark production via $V + A$ currents, then in neutrino reactions

- (i) The increase takes place for $\bar{\nu}_\mu N$ scattering only, and asymptotically $d\sigma(\bar{\nu})/dy|_{y=0} > d\sigma(\nu)/dy|_{y=0}$ (charge symmetry is violated).
- (ii) Both ratios increase for all x provided $E_{\bar{\nu}}, E_\nu$ is high enough.
- (iii) There should be a second component to the dimuons in $\bar{\nu}_\mu N$ scattering arising from the decay of new hadrons via $b \rightarrow u\ell^-\bar{\nu}_\ell$ (the inverse of the production reaction). The rate depends on the unknown ratio of semileptonic to non-leptonic decays of new hadrons containing b .

In addition if flavor changing neutral currents exist we note that

- (i) The effect is most dramatic in $\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu + \dots)$ because of the presence of a $V + A$ coupling.
- (ii) The threshold arises from production of the quark which mixes with u or d , not the quark produced by the corresponding charged current (in our example these

Table 1

New quarks	Valence V + A doublets	Parameters			Remarks
		$\cos \alpha$	$\cos \beta$	η_α	
t	$\begin{pmatrix} t \\ d \end{pmatrix}$	0	1	0	no $\bar{\nu}$ anomaly; poor agreement with NC; large parity violation in atoms
b	$\begin{pmatrix} u \cos \alpha + c \sin \alpha \\ b \end{pmatrix}$	$\cos \alpha$	0	0	gives $ \Delta C = 1$ neutral currents
tb	$\begin{pmatrix} u \cos \alpha + t \sin \alpha \\ b \end{pmatrix}$	$\cos \alpha$	0	0	acceptable if $m_t \gtrsim 3 \text{ GeV}$
tb	$\begin{pmatrix} t \\ d \cos \beta + b \sin \beta \end{pmatrix}$	0	$\cos \beta$	0	no $\bar{\nu}$ anomaly
tb	$\begin{pmatrix} t \\ d \end{pmatrix} \begin{pmatrix} u \cos \alpha + c \sin \alpha \\ b \end{pmatrix}$	$\cos \alpha$	1	0	gives $ \Delta C = 1$ neutral currents
bb'	$\begin{pmatrix} u \\ b \cos \alpha + b' \sin \alpha \end{pmatrix}$	$\cos \alpha$	0	1	$A = 1, B = 0$; cf. Barnett [8], Fayet [15]
tt'	$\begin{cases} \begin{pmatrix} t \\ d \cos \beta + s \sin \beta \end{pmatrix} \\ \begin{pmatrix} t \\ d \sin \beta - s \cos \beta \end{pmatrix} \end{cases}$	0	$\cos \beta$	0	$B = 1$, no $\bar{\nu}$ anomaly

$t b b'$	$\begin{pmatrix} d \cos \beta + b \sin \beta \\ u \cos \alpha + c \sin \alpha \\ b' \end{pmatrix}$	$\cos \alpha$	$\cos \beta$	0	0	gives $ \Delta C = 1$ neutral currents
$t t' b$	$\begin{pmatrix} t \\ d \end{pmatrix} \begin{pmatrix} u \cos \alpha + t' \sin \alpha \\ b \end{pmatrix}$	$\cos \alpha$	1	0	0	$B = 1$
$t t' b$	$\begin{pmatrix} t \\ d \end{pmatrix} \begin{pmatrix} u \cos \alpha + c \sin \alpha \\ b \end{pmatrix}$ $\begin{pmatrix} u \sin \alpha - c \cos \alpha \\ b' \end{pmatrix}$	$\cos \alpha$	0	1	0	$A = B = 1$ (vector neutral current); excluded
$t b b'$	$\begin{pmatrix} u \\ b \end{pmatrix} \begin{pmatrix} t \\ d \cos \beta + s \sin \beta \end{pmatrix}$ $\begin{pmatrix} t' \\ d \sin \beta - s \cos \beta \end{pmatrix}$	0	$\cos \beta$	0	1	$A = B = 1$ (vector neutral current); excluded
$t t' b$ $b b'$	$\begin{pmatrix} u \cos \alpha + t \sin \alpha \\ b \\ t' \\ d \cos \beta + b' \sin \beta \end{pmatrix}$	$\cos \alpha$	$\cos \beta$	0 or 1	0 or 1	A, B general, no $ \Delta C = 1$ neutral currents

were t and b respectively). This means that charged and neutral current thresholds differ.

(iii) Dimuon events (mostly in $\nu_\mu N$ collisions) with equal average μ^- , μ^+ momenta arise from the neutral current decay $t \rightarrow u\mu^+\mu^-$; trimuon events in $\nu_\mu N$ appear from this source [12].

6. Conclusions

If new quark flavors with $V + A$ coupling to valence quarks are needed or desired, low-energy neutral current data constrains the theoretical options. We have studied this in the framework of $SU(2) \times U(1)$ models with the quarks in doublet and singlet representations. It turns out that there exist a large class of models compatible with low-energy data. The favored ones involve mixing quarks in different $SU(2) \times U(1)$ representations and lead to flavor-changing neutral currents. These models also lead to possibly smaller values for the mass of the b -quark often invoked as the explanation for the y anomaly and the recently observed increase of $\sigma(\nu_\mu N \rightarrow \mu^+ + \dots) / \sigma(\nu_\mu N \rightarrow \mu^- + \dots)$.

We have argued that significant charm-changing neutral currents are excluded. If the $(1, 0)$ model is excluded by atomic physics experiments [19], and if the neutral current evidence against models with $B = 1$ is accepted, then of the cases we consider only those with at least six quarks are left. In the event that $0 < A < 1$, $0 < B < 1$, models with seven or more quarks are needed. However, we again remark that models of the kind we consider here are not forced on us by published low-energy data, and will not be until clear evidence against the standard Weinberg-Salam model appears. We can hope that the atomic-physics parity-violation experiments and the coming neutrino and e^+e^- experiments will tell us how much truth there is in all this.

Appendix

We present a shopping list of models which lead to the charged and neutral weak currents in eqs. (3). We limit ourselves to $SU(2) \times U(1)$ models with doublets and singlets of fermions. For quarks this follows by taking quark charges $|e_q| < \frac{4}{3}$, which we will assume. We also exclude doubly charged leptons. We do not discuss the lepton sector; full-scale models can be constructed from the quark sector using the quark-lepton analogy.

Using the GIM mechanism for the LH $(V - A)$ doublets, the main contribution to this part of the doublet structure is

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L.$$

The RH $(V + A)$ doublets must contain one valence quark (this is our main assump-

tion) and one heavy quark (to avoid deviations from the Cabibbo current at low energies.) We ignore possible small non-Cabibbo mixing. All our models thus have ≥ 5 quarks ($u, d, s, c + ?$), and we list only the new ones.

A $V + A$ doublet of the form

$$\begin{pmatrix} c \\ d \end{pmatrix}_R.$$

is already known to be in conflict with experiment, and we disregard it.

Table 1 lists only the minimum number of new quarks needed to generate a given valence current; one is free to add further new quarks not appearing in doublets with valence quarks. We have therefore only listed the relevant valence doublets*. With the mixings we consider some models with at least seven quarks have inescapable vector neutral currents; we list them for completeness. The quarks labelled t, b in eq. (3) must be identified with specific quarks in each model.

References

- [1] Y. Achiman and T.F. Walsh, Heidelberg preprint HD-THEP-76-6 (May 1976); Contribution to 18th Conf. on high-energy physics, Tbilisi, 1976.
- [2] R. Schwitters, 18th Conf. on high-energy physics, Tbilisi, 1976;
B. Wiik, 18th Conf. on high-energy physics, Tbilisi, 1976.
- [3] S.L. Glashow, J. Illiopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285.
- [4] Y. Hara, Phys. Rev. 134 (1964) B701;
J.D. Bjorken and S.L. Glashow, Phys. Letters 11 (1964) 255.
- [5] Y. Achiman, K. Koller and T.F. Walsh, Phys. Letters 59B (1975) 261.
- [6] E.C. Poggio, H.R. Quinn and S. Weinberg, Harvard preprint;
A. De Rujula and H. Georgi, Harvard preprint;
F.E. Close, R.L. Kingsley, G.A. Ringland and D. Sivers, Rutherford Lab. preprint RL-76-021.
- [7] A. Benvenuti et al., HPWF preprints 76/1, 76/2, 76/3, 76/4;
B.C. Barish, talk at Aachen Neutrino Conf., 1976.
- [8] R. Barnett, Phys. Rev. Letters 36 (1976) 1163 and references therein.
- [9] G. Altarelli, G. Parisi and R. Petronzio, Rome preprint.
- [10] R.N. Mohapatra, Phys. Rev. D6 (1972) 2023.
- [11] A. De Rujula, H. Georgi, S.L. Glashow and H.R. Quinn, Rev. Mod. Phys. 46 (1974) 391.
- [12] R.L. Kingsley et al., Phys. Rev. D11 (1975) 1919;
G. Gürsey and P. Sikivie, Phys. Rev. Letters 36 (1976) 775;
P. Raymond, Caltech preprint CALT-68-540.
- [13] S.L. Glashow, Nucl. Phys. 22 (1961) 579;
S. Weinberg, Phys. Rev. Letters 19 (1967) 1264;
A. Salam, Elementary particle physics, ed. N. Svartholm (Stockholm, 1968).
- [14] C. Bouchiat, J. Illiopoulos and P.H. Meyer, Phys. Letters 38B (1972) 519.

* Other doublets can be added as desired, e.g., so as to obtain a model with the same number of $V + A$ and $V - A$ doublets.

- [15] P. Fayet, Nucl. Phys. B76 (1974) 14.
- [16] M. Van Doninck, talk at Aachen Neutrino Conf., 1976.
- [17] F. Bobisut, talk at Aachen Neutrino Conf. 1976;
T. Hansl, talk at Aachen Neutrino Conf., 1976.
- [18] F. Reines, talk at Aachen Neutrino Conf., 1976.
- [19] C. Jarlskog, talk at Aachen Neutrino Conf., 1976;
M.A. Bouchiat and C. Bouchiat, Phys. Letters 48B (1974) 111.
- [20] H. Fritzsch, M. Gell-Mann and P. Minkowski, Phys. Letters 59B (1975) 256;
A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D12 (1975) 3589;
F.A. Wilczek, A. Zee, R.L. Kingsley and S.B. Treiman, Phys. Rev. D12 (1975) 2768;
S. Pakvasa, W.A. Simmons and S.F. Tuan, Phys. Rev. Letters 35 (1975) 703.
- [21] A. Bodek, Thesis, unpublished;
A. Bodek et al., Phys. Rev. Letters 30 (1973) 1087.
- [22] R. Barnett, Harvard preprint.
- [23] C.H. Albright, C. Quigg, R.E. Schrok and J. Smith, FNAL preprints 76/40 and 76/45;
V. Barger, R.J.N. Phillips and T. Weiler, Wisconsin preprints;
J. Kaplan and F. Martin, Paris preprint LPTHE-76-8.
- [24] V. Barger and D. Nanopoulos, Wisconsin preprint.
- [25] T.C. Yang, DESY preprint 76/32.