# FLAVOR CHANGING NEUTRAL CURRENTS AND MULTILEPTONS IN $e^+e^-$ AND $\nu_\mu N$, $\bar{\nu}_\mu N$

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Received 23 November 1976

New quarks and new flavor-changing neutral currents give multiple lepton plus hadron final states in $e^+e^-$, $\nu_\mu N$, $\bar{\nu}_\mu N$. We observe that (i) $e^+e^-$ is a favored place to search for their effects through inclusive ratios $\sigma(e^+e^- + x) \cdot \sigma(\mu^+\mu^- + x) \,.\, \sigma(e^\pm\mu^\mp + x)$ and same sign leptons $e^\pm e^\pm + x$, $\mu^\pm\mu^\pm + x$, $e^\pm\mu^\pm + x$. Above a new flavor threshold four charged lepton final states may become important. (ii) Trilepton final states in $\nu_\mu N$, $\bar{\nu}_\mu N$ are not sensitive to the presence of flavor-changing neutral currents. Much more sensitive are the processes $\bar{\nu}_\mu N \to e^+e^- +$ . and (for charm-changing neutral currents) $\bar{\nu}_\mu N \to e^+ + \ldots$

We recently presented a new class of quark models with V + A charged weak currents coupling light u, d valence quarks to heavy quarks. This happens in a way which leads to *non diagonal* V + A neutral currents [1] [‡1]. A charm-changing neutral current is one example [4]. These models (of $SU_2 \times U_1$ type [5]) are compatible with present inclusive $\nu_\mu N$ and $\bar{\nu}_\mu N$ scattering data at low energy, with $\nu_\mu e^-$, $\bar{\nu}_\mu e^-$ and $\bar{\nu}_e e^-$ scattering, and with preliminary information on parity violation in atoms [1]. More recently, Glashow and Weinberg studied the weak neutral current in $SU_2 \times U_1$ models [6]. They concluded that non-diagonal neutral currents are to be expected in most models with more than the conventional [7] four quarks (u, d, s, c).

There is very preliminary evidence for a new quark beyond charm [8] (and perhaps a new lepton as well [9]). In view of the above remarks, we think it important to look for the signatures produced by new quarks (or charm) coupling to non-diagonal (flavor changing) neutral currents. Lepton plus hadron final states in $e^+e^-$, $\nu_\mu N$, $\bar{\nu}_\mu N$ serve this purpose, as we will show.

Our charged valence quark current has a conventional left-handed piece, plus a new term involving u, d quarks [1],

$$\begin{aligned} J^{c'} &= (\bar{u}b)_R \cos\alpha + (\bar{\underset{\sim}{t}}b)_R \sin\alpha \\ &\quad + (\bar{t}d)_R \cos\beta + (\bar{t}\underset{\sim}{b})_R \sin\beta \end{aligned} \tag{1}$$

($\underset{\sim}{t}$, t or $\underset{\sim}{b}$, b are charge 2/3 or −1/3 quarks, R denotes a V + A current and α, β are mixing angles). The new quarks mixed with u and d are denoted $\underset{\sim}{t}$ and $\underset{\sim}{b}$. Models of this sort are classified in ref. [1]. Of course, one or both of the above terms in (1) may be absent if the corresponding quarks do not exist or do not couple to u, d. The same applies to eq. (2) below.

The orthogonal combinations $\bar{\underset{\sim}{t}} \cos\alpha - \bar{u} \sin\alpha$ or/and $\underset{\sim}{b} \cos\beta - d \sin\beta$ do not occur in $J^{c'}$. Consequently, the neutral current has a flavor-changing piece [1]

$$J^{n'} = \tfrac{1}{4} \sin 2\alpha (\bar{\underset{\sim}{t}}u + \bar{u}\underset{\sim}{t})_R + \tfrac{1}{4} \sin 2\beta (\bar{\underset{\sim}{b}}d + \bar{d}\underset{\sim}{b})_R . \tag{2}$$

If we identify $\underset{\sim}{t} = c$, a charm-changing neutral current results. $|\Delta S| = 1$ neutral currents are excluded ad hoc, using the GIM mechanism for physical quark states [7].

The form of $J^{c'}$ and $J^{n'}$ has some interesting consequences:

(I) The conventional neutral current [10] is nearly V − A, but $J^{n'}$ is V + A. Thus we expect that the muonless scattering ratio $\sigma_n(\bar{\nu}_\mu N)/\sigma_n(\nu_\mu N)$ will rise above $\underset{\sim}{t}$ or $\underset{\sim}{b}$ threshold; $y = E_H/E_{\bar{\nu}}$ distributions in $\bar{\nu}_\mu N \to \bar{\nu}_\mu + \ldots$ will develop a new contribution con-

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[‡1] Subsequently a number of examples have been reported [2, 3].

stant in $y$. Note that $J^{n'}$ is not sensitive to the charge of the new quark. It is important for our arguments later that new flavor production is largest in $\bar{\nu}_\mu$N.

(II) $\underset{\sim}{\mathrm{t}}$ and/or $\underset{\sim}{\mathrm{b}}$ are produced copiously through $J^{n'}$, and decay entirely or mostly via this neutral current [‡2]. It is the quarks t or b which can appear in charged current $\nu_\mu$, $\bar{\nu}_\mu$ reactions. We estimate neutral current decay rates as follows. In the spirit of the parton model we take the decay rate of a hadron to be that of its constituent quark, $\underset{\sim}{\mathrm{t}} \to \ell^+\ell^-\mathrm{u}$ or $\underset{\sim}{\mathrm{b}} \to \ell^+\ell^-\mathrm{d}$. We use two models for the neutral current coupling of $\ell^+\ell^-$: (a) the Weinberg-Salam model (WS) [5]; (b) a model with a pure vector lepton current (VLC) [11]. Ignoring final states masses [‡3]

$$\frac{\Gamma(\underset{\sim}{\mathrm{t}} \to \ell^+\ell^-\mathrm{u})}{\Gamma(\mathrm{c} \to \ell^+\nu_\ell \mathrm{s})} \sim \frac{m_{\underset{\sim}{\mathrm{t}}}^5}{m_\mathrm{c}^5}\,\frac{\sin^2 2\alpha}{8\cos^2\theta_\mathrm{c}}$$

$$\times \begin{bmatrix} Z^{-2}\frac{1}{2}(1+(1-4\sin^2\theta_\mathrm{W})^2]\ (\mathrm{WS}) \\ \\ 2Z^{-2}(1-2\sin^2\theta_\mathrm{W})^2\ (\mathrm{VLC}) \end{bmatrix}. \tag{3}$$

Evidently, $0 \lesssim M_{\ell^+\ell^-} \lesssim m_{\underset{\sim}{\mathrm{t}}}$ and we expect no energy lost in neutrinos; as compensation $\underset{\sim}{\mathrm{t}} \to \nu\bar{\nu}\mathrm{u}$ can occur. These decays always have $|\Delta\ \text{flavor}| = 1$, $\Delta S = 0$. Decays involving $\ell^+\ell^-$ would offer unambiguous evidence for flavor-changing neutral currents. The most dramatic evidence would come from a narrow state decaying to a massive $\ell^+\ell^-$ pair plus hadrons of zero total strangeness. We also expect nonleptonic neutral current decays with $\Delta S = 0$.

(III) Even for a very small $\mathrm{O}(G_\mathrm{F})$ effective neutral current coupling proportional to $\sin 2\alpha$ or $\sin 2\beta$, the neutral mesons $\underset{\sim}{\mathrm{t}}\bar{\mathrm{u}} = \mathrm{M}^\mathrm{o}$ and $\bar{\underset{\sim}{\mathrm{t}}}\mathrm{u} = \overline{\mathrm{M}^\mathrm{o}}$ (or $\mathrm{N}^\mathrm{o} = \underset{\sim}{\mathrm{b}}\bar{\mathrm{d}}$, $\bar{\mathrm{N}}^\mathrm{o} = \bar{\underset{\sim}{\mathrm{b}}}\mathrm{d}$) are fully mixed [12]. Then $\mathrm{M}^\mathrm{o}$ or $\bar{\mathrm{M}}^\mathrm{o}$ ($\mathrm{N}^\mathrm{o}$, $\bar{\mathrm{N}}^\mathrm{o}$) decay equally to $\ell^+\nu_\ell$ + hadrons and $\ell^-\bar{\nu}_\ell$ + hadrons [13]. However, we expect these charged current decays to be suppressed unless $\underset{\sim}{\mathrm{t}} = \mathrm{c}$. We note that complete mixing does not necessarily imply the existence of $\mathrm{O}(G_\mathrm{F})$ flavor-changing neutral currents [12].

Now we take up multilepton signatures in $\mathrm{e^+e^-}$ and $\nu_\mu$N, $\bar{\nu}_\mu$N. First we consider the general case and then specialize to $|\Delta C| = 1$ neutral currents.

*$e^+e^-$ annihilation.* We concentrate on final states with two charged leptons from production and semileptonic decay of a new quark $\underset{\sim}{\mathrm{t}}$. The quark processes are $\mathrm{e^+e^-} \to \bar{\underset{\sim}{\mathrm{t}}} + \underset{\sim}{\mathrm{t}}$ followed by: (i) the charged current decays $\underset{\sim}{\mathrm{t}} \to \ell^+\nu_\ell + \ldots$, $\bar{\underset{\sim}{\mathrm{t}}} \to \ell^-\bar{\nu}_\ell + \ldots$. For $\underset{\sim}{\mathrm{t}} \neq \mathrm{c}$ these are suppressed (see remark II); (ii) the neutral current decay $\underset{\sim}{\mathrm{t}}$ (or $\underset{\sim}{\mathrm{t}}$) → anything. We form the ratios [‡4]

$$\begin{aligned} &\sigma(\mathrm{e^+e^-} + \mathrm{x}) : \sigma(\mu^+\mu^- + \mathrm{x}) : \sigma(\mathrm{e}^\pm\mu^\mp + \mathrm{x}) \\ &\quad = 1 + a : 1 + a : 2\,. \end{aligned} \tag{4}$$

Since $\sigma(\ell^+\ell^- + \mathrm{x})$ requires only one semileptonic decay, it may be large. Correspondingly, we expect this to be small. Events with $\underset{\sim}{\mathrm{t}} \to \nu\bar{\nu} + \mathrm{u}$ will have substantial missing energy, ~2/3 of $m_{\underset{\sim}{\mathrm{t}}}$. Of course, these remarks also apply to $\mathrm{e^+e^-} \to \bar{\underset{\sim}{\mathrm{b}}} + \underset{\sim}{\mathrm{b}}$. The step in $R = \sigma_\mathrm{HAD}/\sigma_{\mu^+\mu^-}$ is, however, smaller than for $\mathrm{e^+e^-} \to \bar{\underset{\sim}{\mathrm{t}}} + \underset{\sim}{\mathrm{t}}$. This tells us whether $\underset{\sim}{\mathrm{t}}$ or $\underset{\sim}{\mathrm{b}}$ appears in (2).

We also expect three and four charged leptons $\ell^+\ell^-\mathrm{e}^\pm + \mathrm{x}$ or $\ell^+\ell^-\mu^\pm + \mathrm{x}$ from neutral + charged current decays and $\ell^+\ell^-\ell'^+\ell'^- + \mathrm{x}$ from neutral current decays, where $\ell, \ell' = \mathrm{e}$ or $\mu$. Note the importance here of distinguishing e and $\mu$.

We estimate that 4 charged lepton final states could even occur at the percent level above a new $\underset{\sim}{\mathrm{t}}$ or $\underset{\sim}{\mathrm{b}}$ flavor threshold beyond charm. Such events would be important evidence for $\underset{\sim}{\mathrm{t}}$ or $\underset{\sim}{\mathrm{b}}$ quarks and their new currents.

It may not be easy to tell leptons from new flavor decays from those arising from charm decays. Note, however, that a sequential heavy lepton cannot give states with $\ell^+\ell^-$ + hadrons. It will also turn out that the 4 charged lepton rate from charm is negligibly small.

In the charm case ($\underset{\sim}{\mathrm{t}} = \mathrm{c}$), we have to modify some of the above remarks. We use (3), and assume a $\lesssim 20\%$ branching ratio $\mathrm{D} \to \mathrm{e}^+\nu_\mathrm{e} + \ldots$ to find $\Gamma(\mathrm{c} \to \mathrm{e^+e^-u})/\Gamma(\mathrm{c} \to \mathrm{e}^+\nu_\mathrm{e} + \ldots) \lesssim 5\%$ and

$$\frac{\Gamma(\text{charm} \to \mathrm{e^+e^-} + \ldots)}{\Gamma(\text{charm} \to \text{all})} \lesssim 1\%, \tag{5}$$

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[‡2] Charged current decays can occur via, e.g., $\underset{\sim}{\mathrm{t}} \to \mathrm{b}\ell^+\nu_\ell$ if $m_\mathrm{b} < m_{\underset{\sim}{\mathrm{t}}}$ or via small mixings with d or u which we ignore here. We assume $\underset{\sim}{\mathrm{t}} \neq \mathrm{c}$; it will turn out that some of these conclusions must be modified if $\underset{\sim}{\mathrm{t}} = \mathrm{c}$ (because of the charged current coupling $(\bar{\mathrm{c}}\delta)_\mathrm{L}$), or if a coupling $(\bar{\underset{\sim}{\mathrm{t}}}\mathrm{s})_\mathrm{R}$ is present. Wrong leptons other than the above must arise from production off sea quarks.

[‡3] $Z \equiv M_{\mathrm{Z}^0}^2 \cos^2\theta_\mathrm{W}/M_\mathrm{W}^2$; the lepton brackets in (3) are ~0.5 for the WS model and ~0.3–0.4 for the VLC model, from ref. [1].

[‡4] We use e–$\mu$ universality. We assume that x contains hadrons; it may also contain neutrinos.

averaged over charmed particles.

This upper limit is for *maximal* $|\Delta C| = 1$ neutral current strength. It can of course vary for different mesons $D^+$, $D^oF^+$.

Despite (5), it is not senseless to search for decays $D \to e^+e^- +$ charged pions. Seen nonleptonic decays like $D^o \to K^-\pi^+$ probably do not have branching ratios much larger than (5) [14] [‡5].

Applying this argument, we find two charged lepton + hadron final states (4) with $a \lesssim 1$. We encourage attempts to measure these ratios. We also find that in $e^+e^-$

$$\frac{\sigma(e^+e^-e^\pm + x)}{\sigma(e^+e^- + x)} \sim 2\frac{\Gamma(c \to e^+e^- + ...)}{(\Gamma(c \to se^+\nu_e)} \lesssim 10\%.$$

The rates for 4 charged leptons are easily seen to be negligible.

Mixing of $D^o - \bar{D}^o$ ($D^o = c\bar{u}$) is very sensitive to $|\Delta C| = 1$ neutral currents even when $a$ in eq. (4) is too small to serve as a diagnostic [13]. We believe that $e^+e^-$ is the favored place to search for $D^o$–$\bar{D}^o$ mixing effects.

It is possible in principle to find the semileptonic branching ratios of $D^o$ and $D^+$, and the amount of $D^o$–$\bar{D}^o$ mixing in $e^+e^-$ interactions [‡6]. To do this we need (i) the charm production cross section; (ii) production ratios $\sigma(D^o\bar{D}^o + ..) : \sigma(D^+D^- + ..) : \sigma(D^+\bar{D}^o + ...) + \sigma(D^-D^o + ...)$; (iii) cross sections $\sigma(e^+ + x)$, $\sigma(e^+e^- + x)$, $\sigma(e^+e^+ + x)$. One can check that the semileptonic branching ratios follow from $\sigma(e^+ + ...)$ and $\sigma(e^+e^- + ...) + 2\sigma(e^+e^+ + ...)$, while $\sigma(e^+e^+ + x)$ then gives the relative rates for $D^o \to e^+\nu_e + ...$ and $D^o (\to \bar{D}^o) \to e^-\bar{\nu}_e + ...$ (i) can be inferred from the increase in $R$ above charm threshold, (ii) hopefully by analysis of the final state [14] and use of isospin relations $\sigma(D^o\bar{D}^o) = \sigma(D^+D^-)$, $\sigma(D^o\bar{D}^{*o}) = \sigma(D^+D^{*-})$ following from charm production via $e^+e^- \to c\bar{c}$. As a special case we note that if mixing is complete and final states in $e^+e^-$ annihilation containing $D^+D^-$ are absent then we predict $\sigma(e^\pm e^\pm + ..) = \sigma(e^+e^- + ...)$.

*Neutrino interactions* [‡7]. Neutral current production of a new flavor, followed by decay via $J^{n'}$ leads to prompt dilepton final states. The quark level processes are $\bar{\nu}_\mu/\nu_\mu q \to \bar{\nu}_\mu/\nu_\mu \underset{\sim}{Q}$ and $\underset{\sim}{Q} \to \ell^+\ell^- q$. Note the distinctive signature $\nu_\mu/\bar{\nu}_\mu N \to e^+e^- + ....$

We expect that trilepton final states via $\bar{\nu}_\mu/\nu_\mu q \to \mu^+/\mu^- + \underset{\sim}{Q}$, followed by $\underset{\sim}{Q} \to \ell^+\ell^- q$, are insensitive to flavor-changing neutral currents. This is because (1) contains no term permitting production of $\underset{\sim}{Q}$ off valence quarks (or s-quarks in the $q\bar{q}$ "sea").

"Wrong" leptons [6] in the final state ($e^\pm$, $\mu^-$ from a $\bar{\nu}_\mu$ beam or $e^\pm$, $\mu^+$ from a $\nu_\mu$ beam) arise via $\bar{\nu}_\mu/\nu_\mu + q \to \underset{\sim}{Q} + \bar{\nu}_\mu/\nu_\mu$, $\underset{\sim}{Q} \to \ell^\pm + ....$ These are also suppressed so long as $\underset{\sim}{t} \neq c$. Then we do not expect wrong lepton final states at an appreciable level. Remember that neutral current production is favored in $\bar{\nu}_\mu$ beams. We find a pattern of favored and disfavored signatures (ignoring the $q\bar{q}$ sea in the nucleon)

$\bar{\nu}_\mu N \to \bar{\nu}_\mu e^+ + ..$ (favored)
$\nu_\mu N \to \nu_\mu e^+ + ...$ (disfavored)
$\nu_\mu \to \nu_\mu \mu^+$ (disfavored)

($\underset{\sim}{t}$ produced)

$\bar{\nu}_\mu N \to \bar{\nu}_\mu e^- + ..$ (favored)
$\bar{\nu}_\mu N \to \bar{\nu}_\mu \mu^- + ...$ (favored)
$\nu_\mu N \to \nu_\mu e^- + ...$ (disfavored).

($\underset{\sim}{b}$ produced)

From the distribution of "slow" muons in dimuon events [15] we expect the above wrong leptons to carry off $\lesssim 10\%$ (5%) of the incident $\bar{\nu}_\mu(\nu_\mu)$ energy on the average. This only applies well above $\underset{\sim}{t}$, $\underset{\sim}{b}$ threshold.

Some of these statements have to be modified if charm-changing neutral currents exist. This is because of the large charged current coupling $(\bar{c}s)_L$.

(i) Dileptons. These can amount to at most $10^{-2}$ of $\sigma(\bar{\nu}_\mu N)$, because of (5). For $\nu_\mu N$ charm production via

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[‡5] Nonleptonic neutral current decays might show up as violations of charm ratios like $\Gamma(D^o \to \pi^+\pi^-)/\Gamma(D^o \to K^-\pi^+) \approx \tan^2\theta_c$.

[‡6] Above threshold for $D^o$, $D^+$ production and below threshold for $F^+$, and assuming *CP* invariance.

[‡7] Some of this has been noted independently by V. Barger and D. Nanopoulos [3].

$J^{n'}$ is smaller and we estimate a dilepton fraction $\lesssim 10^{-3}$.

(ii) Trileptons. Again, trileptons in $\bar{\nu}_\mu N$ or $\nu_\mu N$ are a very insensitive test for $|\Delta C| = 1$ neutral currents. From an estimate of 5–10% charm production by the charged current, combined with (5), we estimate a trilepton fraction $\lesssim 10^{-3}$. We again emphasize that these upper bounds assume *maximal* $|\Delta C| = 1$ neutral currents in our models.

(iii) Wrong leptons. This is a favorable signature for $|\Delta C| = 1$ neutral currents. We estimate that for $\sin 2\alpha = 1$, $\bar{\nu}_\mu N \to e^+ + \ldots$ could reach several percent of $\sigma(\bar{\nu}_\mu N)$. The corresponding estimate for $\nu_\mu N \to e^+ + \ldots$ or $\mu^+$ is several times $10^{-3}$. There exists a limit at the $10^{-3}$ level for $\sigma(\nu_\mu \to \mu^+)/\sigma(\nu_\mu \to \mu^-)$ [16]. This does not appear to us to be incompatible with our expectations, even for moderately large $\sin 2\alpha$ [‡8].

We look forward to experimental limits on the multilepton signatures we have been describing. These may be expected soon for charm-changing neutral currents. For the case of new flavors, our considerations may be of modest interest to those designing experiments, particularly $e^+e^-$ annihilation experiments for PETRA or PEP. Good simultaneous electron and muon identification seems essential.

We thank M. Krammer, A. Mann and B. Wiik for comments, and T.C. Yang and B.-L. Young for reading the manuscript.

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[‡8] In ref. [1] we argued that present neutrino cross section data already made it unlikely that $|\Delta C| = 1$ neutral currents are maximal.

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