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Diagonal neutral currents*

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General conditions are derived for neutral currents to be diagonal in all quark fields. The solution is a generalization of the Glashow-Iliopoulos-Maiani scheme to many quark fields with two distinct charges. It is shown that the diagonality and universality of the neutral operator is preserved by leading terms of the single-loop diagrams. In contrast to the basic assumption of this article, neutral-current charm-changing transitions lead to apparent $|\Delta S|=1$ neutral currents, apparent lepton-number violation, and large D^0-$\bar{D}^0$ mixing. The article also describes a sum rule, which is independent of the number of quarks, and surveys the experimental status of charm-changing neutral currents.

I. INTRODUCTION

In gauge theories of the weak and electromagnetic interactions the structure of the neutral currents reflects to a large extent the symmetry structure of the charged currents. Now that it is evident, from numerous experiments, that electron-positron annihilation and neutrino-induced reactions excite states with new quantum numbers, it is timely to investigate several properties of the neutral currents which are direct reflections of the new components of the charged currents.

The guiding principle of the investigation is the new ansatz, proposed at the Aachen conference,[1] that neutral currents are diagonal in all quark fields. This hypothesis is motivated by the suppression of strangeness-changing neutral currents in low-energy transitions. It is satisfied in the leptonic sector, and its extension is implied by the quark-lepton analogy,[2] which has been proven quite useful in the past. It is also naturally satisfied in the models which introduced charm[2-4] into weak interactions. To satisfy this proposal we find that there are several constraints, which are subject to experimental examination.

Section II introduces the problem and describes a general solution. The solution is a generalization of the Glashow-Iliopoulos-Maiani scheme[3] which eliminates flavor-changing transitions. It is then shown that universality and diagonality is preserved by leading contributions of the single-loop diagrams. Section III gives specific examples in six-quark models. The last section compares the assumptions and some of their consequences with experiment. If neutral currents change flavor they will produce some remarkable effects. For instance, charm-changing neutral currents will produce apparent $|\Delta S|=1$ transitions, a proliferation of neutral-current events with strange particles at the 50% level and neutrino- (antineutrino-) induced reactions resulting in a wrong-sign muon. Similar effects arise in electron-positron annihilation. A survey of the experimental status concludes that charm-changing neutral couplings are smaller than the observed conventional neutral couplings, but presently the bounds are not very restrictive.

II. GENERAL CONDITIONS

The requirement that the neutral operators of a gauge theory are diagonal in all quark fields dictates to a large extent the representation assignment for the fermion fields. This section describes such conditions in an $SU(2)\times U(1)$ gauge theory.

Consider a model with $2N$ quark fields, where half of them carry charge Q and the other half carry lower charge $(Q-1)$. Consider the set of quarks with definite flavors, i.e., a representation where the quark mass matrix is diagonal. At this stage the representation assignment of the quarks under the weak group $SU(2)\times U(1)$ is arbitrary, i.e., they are not necessarily all SU(2) doublets. The charge-raising current[5] is defined as

$$j^+ = \psi_L^\dagger \tau^+ \otimes M\psi_L\ , \tag{2.1}$$

where ψ_L is a column matrix in the left-handed quark fields

$$\psi_L = \begin{bmatrix} c \\ t \\ \vdots \\ \mathcal{P} \\ \mathfrak{N} \\ \lambda \\ \vdots \\ b \end{bmatrix}\ , \tag{2.2}$$

τ^+ is a 2×2 Pauli matrix, and M is a real $N\times N$ matrix.[6] The commutator of this current with its Hermitian adjoint gives a neutral operator

$$j^0=[j^+,j^-]$$
$$=\bar{\psi}_L(\tfrac{1}{2}\{\tau^+,\tau^-\}\otimes[M,M^\dagger]+\tfrac{1}{2}[\tau^+,\tau^-]\otimes\{M,M^\dagger\})\psi_L\,. \tag{2.3}$$

The diagonality of the neutral operator is equivalent to the conditions

$$MM^\dagger=d_1\,, \tag{2.4}$$

$$M^\dagger M=d_2\,, \tag{2.5}$$

where d_1 and d_2 are diagonal matrices.

Closing of the algebra generated by the above currents implies

$$MM^\dagger M=M\,. \tag{2.6}$$

If M is a nonsingular matrix then it follows that

$$d_1=d_2=d, \tag{2.7}$$

which is a multiple of the unit matrix. On the other hand, if M is singular then

$$\det d_2=(\det M)^2=0\,.$$

This means that at least one of the diagonal elements of d_2 must be zero, and implies that the corresponding quark decouples from the currents $j^\pm$ and j^0. However, I obtain the same solution if in addition to diagonality I impose the universality[7] condition

$$\sum_{\text{over } j \text{ only}} M_{ij}M^\dagger_{ji}=\text{constant}\,, \tag{2.8}$$

independent of i. This elegant solution is the most general in the case considered and provides a natural extension of the Glashow-Iliopoulos-Maiani scheme to an arbitrary number of quark fields.

It is now important to check that the lowest-order selection rules are also preserved by the leading contributions of single-loop diagrams, and that universality is also preserved; that is, single-loop corrections yield a *common* renormalization constant to each of the various observed coupling constants. These conditions are satisfied by the class of models considered and follow from the algebraic structure of the currents:

$$\{j^+,j^-\}=\frac{1-\tau_3}{2}\otimes d_1+\frac{1+\tau_3}{2}\otimes d_2\,, \tag{2.9}$$

$$j^+j^0j^-=(1-\tau_3)\otimes(d_2)^2\,, \tag{2.10}$$

$$j^-j^0j^+=(1+\tau_3)\otimes(d_1)^2\,. \tag{2.11}$$

It follows from Eqs. (2.4) and (2.5) that the right-hand sides of Eqs. (2.9)–(2.11) are again diagonal matrices and consequently conserve the flavor quantum numbers. This property is independent of the explicit representation of the M's or for that matter of Eq. (2.7). The diagrams which could, in principle, spoil the diagonality of the neutral operator are shown in Fig. 1. I consider leading contributions and neglect terms of order $\alpha G(m/M_W)^2$, where m is a quark or lepton mass. Diagrams with two adjacent charged vertices like (a) and (b) will yield diagonal effective vertices by virtue of Eqs. (2.3) and (2.9). Vertex corrections will also yield an effective operator diagonal in the quark flavor by virtue of Eqs. (2.10) and (2.11).

In order to obtain a *common* correction to the various quark couplings, I impose condition (2.7), which leads to

$$j^0=[j^+,j^-]=\bar{\psi}\tau_3\otimes d\psi,\quad \{j^+,j^-\}=\bar{\psi}\underline{1}\otimes d\psi\,, \tag{2.12}$$

$$j^+j^0j^-=(1-\tau_3)\otimes d^2,\quad j^-j^0j^+=(1-\tau_3)\otimes d^2\,. \tag{2.13}$$

Now the corrections for the different quark flavors are the same. The above algebraic relations are general and are useful in studying diagonality and universality to higher orders.

The analysis so far is general and applies to left-handed, as well as right-handed, quark multiplets. In order to agree with the physical obervations, however, one must impose additional constraints to some of the matrix elements. These constraints are different for multiplets of different helicities, and I discuss them separately.

Left-handed sector

The Cabibbo form of the weak current determines the coupling

$$\bar{\mathcal{P}}(\mathfrak{N}\cos\theta_C+\lambda\sin\theta_C+\cdots)\,, \tag{2.14}$$

where the dots stand for the coupling to additional

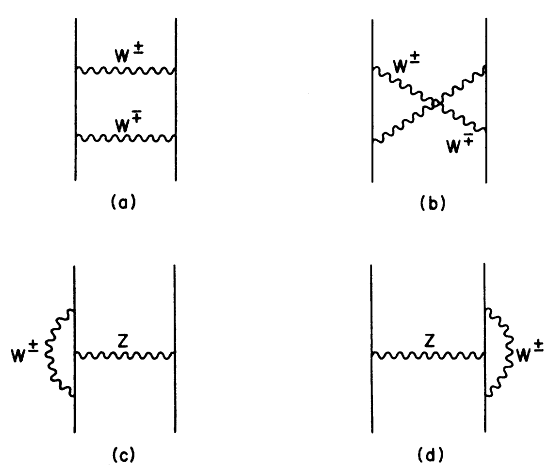

FIG. 1. Single-loop diagrams which may produce off-diagonal elements for neutral currents.

quarks. It is convenient to introduce a new basis for the quarks

$$\psi_L' = \begin{bmatrix} c \\ t \\ \vdots \\ \mathcal{P} \\ \mathfrak{N}_C \\ \lambda_C \\ \vdots \\ b \end{bmatrix}, \tag{2.15}$$

with $\mathfrak{N}_C = \mathfrak{N}\cos\theta_C + \lambda\sin\theta_C$ and $\lambda_C = -\mathfrak{N}\sin\theta_C + \lambda\cos\theta_C$. The two bases are related by a unitary transformation. The effect on the charge-raising current is to replace the matrix M by a new matrix $\tilde{M}$ which is again unitary. The element of $\tilde{M}$ corresponding to the $\bar{\mathcal{P}}\mathfrak{N}_C$ coupling is one (or close to one),[8] while that of the $\bar{\mathcal{P}}\lambda_C$ must be zero. There are two general consequences.

(a) Let j_Δ^+ be the charged current which is obtained from the general current by deleting the $\bar{\mathcal{P}}\mathfrak{N}_C$ term. Then the commutator

$$[j_\Delta^+, j_\Delta^-] = \tfrac{1}{2}(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})\sin^2\theta_C + \dots ; \tag{2.16}$$

that is, the overall strength of the term with the quark content $(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})$ is determined.

Proof: The contribution of the Cabibbo current is represented in the notation of Eq. (2.1) by the matrix M_1 with

$$(M_1)_{ij} = \delta_{iN}\delta_{j1}, \quad (M_1^\dagger)_{ij} = (M_1)_{ji} = \delta_{jN}\delta_{i1}; \tag{2.17}$$

then

$$j_\Delta^+ = \bar{\psi}'\,\tau^+ \otimes (\tilde{M} - M_1)\psi' \tag{2.18}$$

and

$$[j_\Delta^+, j_\Delta^-]_{iK} = \frac{1}{2}\begin{pmatrix} \{\tilde{M},\tilde{M}^\dagger\}_{iK} - 2\tilde{M}_{i1}\delta_{KN} - 2\delta_{iN}\tilde{M}_{1K}^\dagger + 2\delta_{iN}\delta_{KN} & 0 \\ 0 & -\{\tilde{M},\tilde{M}^\dagger\}_{iK} + 2\tilde{M}_{NK}\delta_{i1} + 2\tilde{M}_{iN}^\dagger\delta_{K1} - 2\delta_{i1}\delta_{KN} \end{pmatrix}. \tag{2.19}$$

The contributions to the commutator from the $\bar{\mathcal{P}}\mathcal{P}$ and $\bar{\mathfrak{N}}\mathfrak{N}$ bilinears are

$$[j_\Delta^+, j_\Delta^-] = [\tfrac{1}{2}\{\tilde{M},\tilde{M}^\dagger\} - 1](\bar{\mathcal{P}}\mathcal{P} - \bar{\mathfrak{N}}\mathfrak{N}) + \tfrac{1}{2}(\bar{\mathcal{P}}\mathcal{P} - \bar{\mathfrak{N}}\mathfrak{N})\sin^2\theta_C - \tfrac{1}{2}(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})\sin^2\theta_C + \cdots . \tag{2.20}$$

This commutation relation can be translated into a fixed-Q^2 sum rule[9] stating that neutrino and antineutrino induced structure functions on an isoscalar target must satisfy the relation

$$\int_{\text{threshold}}^{\infty} [W_2^{\nu d}(Q^2,\nu) - W_2^{\bar{\nu} d}(Q^2,\nu)]_{\Delta Q \neq 0}\, d\nu = \tfrac{1}{2}\sin^2\theta_C \langle d|(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})|d\rangle$$
$$= 3\sin^2\theta_C . \tag{2.21}$$

The subscript $\Delta Q \neq 0$ means that the structure functions correspond to transitions which produce states with new quantum numbers over and beyond strangeness. The important feature is that the right-hand side contains the square of the sine of the Cabibbo angle, which implies that if the production of final states with new quantum numbers is substantial, the structure functions $W_2^{\nu d}$ and $W_2^{\bar{\nu} d}$ must be equal on the average. In quark-parton models the sum rule is rewritten as an integral of the scaling variable and is discussed later on.

(b) The neutral operator j^0 does not have an isoscalar component with the content $(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})$. The absence of this term frequently survives in the final form of the neutral current. For instance, if the mixing in the theory is such that the neutral current is an admixture of j^0 and the electromagnetic current, then a $(\bar{\mathcal{P}}\mathcal{P} + \bar{\mathfrak{N}}\mathfrak{N})$ axial-vector current component is absent. Such a component can be detected in experiments sensitive to the effective charges of neutral currents, i.e., elastic neutral-current form factors at $Q^2 = 0$. For proton and neutron targets only the isovector and the strong-SU(2) isoscalar form factors survive at $Q^2 = 0$.

(c) Relation (2.10) holds for all rows of the matrix M. The observed Cabibbo theory implies that the coupling of $\mathcal{P}$ quarks to other quarks besides $\mathfrak{N}_C$ is small or zero.[8] In contrast, the coupling of charm or other quarks with charge Q to new heavy quarks can be substantial. Thus if a measurement of the charmed-quark couplings reveals a substantial deviation from 1 it implies the existence of new heavy quarks. Explicit models have been constructed with such properties and will be reviewed in the next section.

Right-handed sector

There are constraints to be imposed on the right-handed couplings of the matrix M_R.

(i) The $\overline{\mathcal{P}}_R\mathfrak{N}_R$ coupling is not allowed from β-decay observations and the observed $\sigma^{\bar\nu}/\sigma^{\nu}$ ratio at medium-high energies ($E_\nu \leq 30$ GeV).

(ii) A $\overline{\mathcal{P}}_R\lambda_R$ coupling is not allowed by the hyperon decays.

(iii) An analysis of decays relevant for the $\Delta I = \frac{1}{2}$ rule by Golowich and Holstein[10] requires that a right-handed $\mathfrak{N}$-quark coupling to an isoscalar quark, i.e., $\overline{X}\gamma_\mu(1+\gamma_5)\mathfrak{N}$, is allowed only if $\overline{\lambda}\gamma^\mu(1\pm\gamma_5)x$ is absent.

Conditions (i) and (ii) indicate that right-handed currents necessarily excite new quantum numbers, and the neutral operator, which they generate, does not contain any isoscalar part with the content $(\overline{\mathcal{P}}\mathcal{P}+\overline{\mathfrak{N}}\mathfrak{N})$. This means that the sum rule analogous to Eq. (2.21) for currents of right-handed chirality has a zero on the right-hand side.

At this point, it is worthwhile to summarize the approach. It is assumed that a theory of the weak interactions can be constructed from a set of quark fields. For technical simplicity, I assumed that half of the quarks carry charge Q and the other half charge $Q-1$. A general charge-raising current was constructed, and the following was assumed.

(1) The charge-lowering current is given by its Hermitian adjoint.

(2) The algebra of the above currents and those generated by them closes. This essentially means that the currents couple to a limited number of intermediate vector bosons. In our case the algebra of the charged currents closes with the neutral operator j^0. It requires only three W bosons, which is an attractive possibility.

(3) The neutral operator generated by the commutator of the charged currents is diagonal in all quark fields.

(4) Universality is satisfied by quark fields of the same chirality. Assumptions 1, 2, and 4 seem general enough and are obeyed in a wide class of models. Assumption (3) is a generalization of the observed suppression for strangeness changing neutral currents. It is an additional postulate that leads to numerous predictions which can now be tested by experiment.

The previous discussion is motivated by the successes of gauge theories and will be useful to extend it into a complete and renormalizable model. If the renormalization is achieved by a Higgs mechanism, then special conditions must be imposed, so that its presence does not spoil the diagonality of the neutral current. I did not yet investigate the conditions required by either the Higgs mechanism or the rest of the theory for diagonality to be again preserved. It is observed, however, that this section is logically self-consistent and could stand by itself.

III. AN EXAMPLE: SIX-QUARK MODELS

Consider a state of six left-handed quark fields

$$\psi_L = \begin{bmatrix} c \\ t \\ \mathcal{P} \\ \mathfrak{N}_C \\ \lambda_C \\ b \end{bmatrix} \tag{3.1}$$

with three quarks $(c, t, \mathcal{P})$ carrying charge Q and the other three carrying charge $Q-1$. The general form of M_L is

$$M_L = \begin{pmatrix} \beta\sin\alpha & -a\cos\alpha & -\sin\alpha \\ -\beta\cos\alpha & -a\sin\alpha & \cos\alpha \\ 1 & 0 & \beta \end{pmatrix}, \tag{3.2}$$

where α, β, and a are real parameters subject to the condition $a^2 = 1+\beta^2$. The universality condition suggests that β is small,[8] but the coupling $\bar{c}b$ could still be large and depends only on α. Precise measurements of semileptonic decays of charmed particles can determine these couplings. If the universality condition (2.10) of the left-hand sector is not saturated by a large amount, it will be necessary to introduce the heavy quark b.

Explicit calculation of the time components of the commutator $[j_\Delta^+, j_\Delta^-]$ verifies Eq. (2.20) and leads to the sum rule. If in addition we assume scaling on the variable

$$\xi = Q^2/2M\nu, \tag{3.3}$$

where M is the nucleon mass, the sum rule takes the form

$$\int [F_2^{\nu d}(\xi) - F_2^{\bar\nu d}(\xi)]_{\Delta Q\neq 0}\frac{d\xi}{\xi} = \tfrac{1}{2}\sin^2\theta_C\langle d\,|(\overline{\mathcal{P}}\mathcal{P}+\overline{\mathfrak{N}}\mathfrak{N})|\,d\rangle = 3\sin^2\theta_C\,. \tag{3.4}$$

In the quark-parton model and in the deep-inelastic region the difference of the structure functions is a positive-semidefinite quantity. The positivity condition implies that

$$\int [F_2^{\nu d}(\xi) - F_2^{\bar\nu d}(\xi)]_{\Delta Q\neq 0}\,\xi^n d\xi \leq \int [F_2^{\nu d}(\xi) - F_2^{\bar\nu d}(\xi)]_{\Delta Q\neq 0}\frac{d\xi}{\xi} = 3\sin^2\theta_C \tag{3.5}$$

for n zero or positive. Consequently, it implies that the difference of integrals for the structure functions must be at most $3\sin^2\theta_C$.

For quarks with right-handed chirality the conditions of the previous section give a very restrictive form. In fact, if we adopt the point of view that the $\bar{c}\lambda$ coupling has already been observed, then

$$M_R = \begin{pmatrix} 0 & A & 0 \\ A & 0 & 0 \\ 0 & 0 & A \end{pmatrix} . \tag{3.6}$$

The parameter A depends on the group structure of the theory. For instance, if the group is only SU(2), then $A^2 = 1 + \beta^2$. But it is also possible to have sectors of different chiralities governed by different groups, as is the case of $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$, and A is now a new coupling constant. In any case, M_R does not contribute to the sum rule.

For $A^2 = 1 + \beta^2$, $\beta = 0$, $a = -1$, and $\alpha = 0°$ we recover the six-quark model of the vectorlike theories.[11]

IV. COMPARISONS WITH EXPERIMENTS

The hypothesis that the neutral current is diagonal in the quark fields can already be tested, to a limited extent, by experiment. If nondiagonal matrix elements are present, they produce several distinct phenomena. Let us assume, for the moment, that charm-changing neutral currents are present and then deduce constraints on their effective coupling constants. The presence of the couplings[12]

$$\nu\mathcal{P} \to \nu c \,, \tag{4.1}$$

$$\bar{\nu}\mathcal{P} \to \bar{\nu}c \tag{4.2}$$

will give rise to threshold phenomena by increasing the absolute neutral-current (NC) cross section above the charm threshold. We assume an effective interaction of the form

$$\mathcal{L} = \frac{G}{\sqrt{2}}\, \bar{U}\gamma_\mu(1-\gamma_5)U\bar{c}\gamma^\mu(h_V + h_A\gamma_5)\mathcal{P} \;, \tag{4.3}$$

and define $h_\pm = h_V \pm h_A$. At high energies the new contribution to the total cross section can be estimated in the parton model in terms of the quark distribution functions. The cross section per nucleon for isoscalar targets is given by

$$\left.\frac{d\sigma}{dx\,dy}\right|_{\Delta Q \neq 0} = \frac{G^2ME}{4\pi}\,[u(x) + d(x)][(1-y)^2 h_+{}^2 + h_-{}^2] \,. \tag{4.4}$$

Thus the ratio of the total cross section is

$$\rho = \frac{\sigma_{\mathrm{NC}}^{\Delta Q \neq 0}}{\sigma_{\mathrm{NC}}^{\mathrm{tot}}} = \frac{\frac{1}{3}h_+{}^2 + h_-{}^2}{(\frac{1}{3}g_+{}^2 + g_-{}^2) + (\frac{1}{3}g_+'{}^2 + g_-'{}^2) + (\frac{1}{3}h_+{}^2 + h_1{}^2)} \,, \tag{4.5}$$

where in the Weinberg-Salam model

$$g_+ = -\tfrac{4}{3}\sin^2\theta_W \,, \quad g_- = 1 - \tfrac{4}{3}\sin^2\theta_W \,, \tag{4.6}$$

$$g_+' = -\tfrac{2}{3}\sin^2\theta_W, \quad g_-' = 1 - \tfrac{2}{3}\sin^2\theta_W \,. \tag{4.7}$$

For values of $h_\pm$ equal to $g_\pm$ or $g_\pm'$ one finds $\rho \approx 0.35$.

Furthermore, since the charmed particles decay predominantly into strange particles,[13-15] we expect an equal increase of strange particles in the final state. This will result in a sudden increase of neutral-current events with strange particles over and above that of associated production. Associated production of strangeness in neutral-current events was estimated[16] to be at the 15–20% level. Consequently, if at high energies the percentage of events with strange particles in neutral-current events increases to the 50–60% level it will strongly suggest the presence of the couplings (4.1) and (4.2). In this case a good fraction of the events will have apparent $|\Delta S| = 1$ transitions. If, on the other hand, the percentage of events with strange particles is at the 15–20% level, it could be explained by conventional production schemes. An experimental result has been reported for the ratio

$$\sigma_{\mathrm{NC}} \text{ (with strange parts)}/\sigma_{\mathrm{NC}} \approx 14\% \tag{4.8}$$

by the Gargamelle collaboration.[17] It is close to the value expected from associated production. The energy of this experiment, however, is too low for copious production of charmed particles. Thus a similar ratio at high energies is very important.

The sequential decay[18,19]

$$\nu N \to \nu c + x$$
$$\searrow \mu^+ \nu + \text{hadrons} \tag{4.9}$$

will produce muons of the wrong sign with an apparent lepton-number violation. Early searches for W's and heavy leptons by neutrinos indicated[20] that in a sample of 1522 charged neutrino interactions there were eight events with fast muons of the wrong sign. Even though most of the wrong-sign muons could be accounted for, we may still consider this number as an upper bound. Then

$$\sigma(\nu N \to \nu c + x)B/\sigma_{\mathrm{ch}} = \tfrac{1}{4}B(\tfrac{1}{3}h_+{}^2 + h_-{}^2) \leq 0.005 \,. \tag{4.10}$$

For $B = \frac{1}{10}$ this is smaller than the conventional neutral-current coupling, but not very restrictive.

It is evident from the previous two estimates that present data already impose restrictions, which are subject to considerable improvements. The capabilities of the previous measurements, however, are limited because associated production of either charmed states or strange particles reproduces some of the phenomena, but at a smaller level.

Associated production of charm is already a limiting factor in the interpretation of the trimuon events, i.e.,

$$\nu N \to \mu^- \mu^+ \mu^- X . \tag{4.11}$$

Events of this type arising from charmed pairs are expected[21,22] at a level of 10^{-3}–10^{-4} of the charged-current neutrino interactions. This seems to be an upper bound for trimuons from the reaction

$$\nu + N \to \mu^- + D + X, \quad D \to \mu^+ \mu^- . \tag{4.12}$$

Production of D is estimated at the 10% level, but the branching ratio

$$B = \frac{\Gamma(D \to \mu\bar{\mu})}{\Gamma(D \to \text{all})}$$

is suppressed by standard helicity arguments. Thus the absolute rate of the trimuon events alone cannot distinguish between reactions (4.11) and (4.12). With a large number of trimuon events one can plot dimuon mass distributions and look for an enhancement of the D-mass region.

Direct nondiagonal couplings will also result in a large mass splitting of the D_1-D_2 system and considerable mixing. The striking consequences,[18,22,23] already discussed in the literature, is that pairs of $D_0\bar{D}_0$ would decay not only into $(K^-\mu^+\nu)(K^+\mu^-\bar{\nu})$ but also into $(K^+\mu^-\bar{\nu})(K^+\mu^-\bar{\nu})$ and $(K^-\mu^+\nu)(K^-\mu^+\nu)$ pairs and similar nonleptonic decay modes. The result will be apparent $|\Delta S| = 2$ transitions in both electron-positron annihilation and neutrino-induced reactions.

Other consequences of diagonal neutral currents are much harder to test. The sum rule (2.21) must hold for each value of Q^2 independent of any scaling hypothesis. At this time the limited statistics allow only an indirect check. Since the data are consistent with the general expectations of the parton model, they are also consistent with the sum rule which is naturally incorporated into the model.

The effective charges of the neutral currents are measurable in experiments that observe neutral-current effects in atomic transitions. These experiments measure the coherent nuclear matrix element of neutral currents and are capable of distinguishing axial-vector and vector, as well as isoscalar and isovector, components. Atomic experiments are far from producing the detailed effects needed for this investigation.

Note added. After the completion of this work I was informed of an article by Glashow and Weinberg dealing with diagonal neutral currents in SU(2) $\times$ U(1) gauge theories.[26]

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[5]The operators occuring in this article are charges or time components of currents and I adopt a compact notation by suppressing the Dirac matrices. The Lagrangian of the system is written as

$$\mathcal{L} = \mathcal{L}_w + \mathcal{L}_s + \bar{\psi}\,\mathfrak{M}\psi ,$$

where $\mathcal{L}_w$ is invariant under the weak group G_w, $\mathcal{L}_s$ is invariant under the strong group G_s, and $\mathfrak{M}$ is the mass matrix. The quark fields occurring in Eq. (2.2) are those for which the mass matrix is diagonal.

[6]The matrices considered are real, and the theory conserves CP.

[7]In six-quark models H. Harari, Phys. Lett. 57B, 265 (1975), points out that an orthogonal M leads to diagonal neutral currents. The present article addresses the converse problem: If the neutral currents are diagonal, what are the minimal constraints imposed on M in a consistent theory of weak interactions.

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