PHYSICAL REVIEW D VOLUME 15, NUMBER 7 1 APRIL 1977

Natural conservation laws for neutral currents*

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(Received 20 August 1976)

We explore the consequences of the assumption that the direct and induced weak neutral currents in an $SU(2)\otimes U(1)$ gauge theory conserve all quark flavors *naturally*, i.e., for all values of the parameters of the theory. This requires that all quarks of a given charge and helicity must have the same values of weak T_3 and $\vec{T}^2$. If all quarks have charge $+2/3$ or $-1/3$ the only acceptable theories are the "standard" and "pure vector" models, or their generalizations to six or more quarks. In addition, there are severe constraints on the couplings of Higgs bosons, which apparently cannot be satisfied in pure vector models. We also consider the possibility that neutral currents conserve strangeness but not charm. A natural seven-quark model of this sort is described. The experimental consequences of charm nonconservation in direct or induced neutral currents are found to be quite dramatic.

I. INTRODUCTION

It has been known for many years that there are no strangeness-changing neutral-current weak interactions, or none with anything like the strength of the familiar charged-current weak interactions. We see this from the slowness of such decays as $K_L^0 \to \mu^+\mu^-$ and $K^+ \to \pi^+\nu\bar{\nu}$, and even more strongly (and independently of the nature of the lepton couplings) from the size of the K_1^0-K_2^0 mass difference. For this reason, until strangeness-conserving neutral-current weak interactions were discovered in 1973,[1] many physicists were inclined to doubt their existence in any form.

The observed suppression of the strangeness-changing neutral currents is so dramatic numerically that we find it hard to believe that it comes about because the parameters of the theory just happen to take certain values. We would prefer instead to believe that the conservation of strangeness by the neutral currents is *natural*, that is, that it follows from the group structure and representation content of the theory, and does not depend on the values taken by the parameters of the theory.

The gauge theory[2] that uses four quark flavors is natural in this sense, but many of the gauge theories proposed recently are not. In some of these theories, the conservation of strangeness by the first-order neutral-current interaction must be arranged by a careful tuning of quark masses and mixing angles. Even after the parameters of the theory are chosen in this way, weak radiative effects can sometimes produce corrections to the quark mass of order α, leading to strangeness-changing neutral currents of order αG_F. In other theories, there are no strangeness-changing neutral currents, but the exchange of pairs of charged intermediate bosons can induce an effective strangeness-changing neutral current of order αG_F. In still other theories, the exchange of Higgs bosons can produce a strangeness-changing neutral current of roughly the same order. In principle these effects may perhaps be eliminated by a retuning of the parameters of the theory (including in the last case the parameters of the Higgs-boson interactions), but we would find a theory much more attractive if the neutral currents conserved strangeness naturally.

In this paper we explore the implications of the condition that the conservation laws obeyed by the neutral current of $SU(2)\times U(1)$ gauge theories are obeyed naturally. In Secs. II and III we consider a general $SU(2)\otimes U(1)$ gauge theory, and demand that the neutral-current interactions conserve all quark flavors naturally: strangeness, charm, and whatever additional flavors may turn out to be necessary. We deduce the necessary and sufficient conditions for this: All quarks of fixed charge and helicity must (1) transform according to the same irreducible representation of weak SU(2), (2) correspond to the same eigenvalue of weak T_3, and (3) receive their contributions in the quark mass matrix from a single source (either from the vacuum expectation value of a single neutral Higgs meson or from a unique gauge-invariant bare mass term). Examples satisfying these very restrictive conditions are discussed. If we limit ourselves to models involving quarks of charges $\frac{2}{3}$ and $-\frac{1}{3}$ exclusively, the only acceptable possibilities with natural flavor conservation to order αG are these: all left-handed quarks in weak doublets and all right-handed quarks in singlets; all quarks of each helicity in doublets. For the latter case (the purely vector model), flavor-changing neutral-current effects due to Higgs exchange cannot naturally be excluded. In Sec. IV we relax our condition, and demand only that the neutral-current interactions conserve strangeness naturally, for this is the only conservation law yet established by experiment. We discuss an amusing seven-quark model satisfying the relaxed condition. In Sec. V we explore the experimental consequences of relaxing the conservation law for charm by neutral-current interactions. These consequences turn out to be quite dramatic. We may soon be in a position to say whether or not the neutral currents do conserve charm, as they do strangeness.

II. ON THE NATURAL ABSENCE OF FLAVOR-CHANGING NEUTRAL-CURRENT INTERACTIONS

For the sake of simplicity and concreteness, we will restrict ourselves throughout this paper to the familiar SU(2) × U(1) gauge theory of weak and electromagnetic interactions, though our remarks have obvious extensions to other gauge theories. Also, we will tacitly assume that the strong interactions are generated by unbroken color SU(3) gauge interactions, but we will suppress color indices everywhere. For the moment, we will put no restriction on the numbers and charges of the quarks in the theory.

The neutral intermediate boson Z will in general couple to a hadronic neutral current of the form

$$J_z^\mu = \bar{q}\gamma^\mu(1+\gamma_5)Y_L q + \bar{q}\gamma^\mu(1-\gamma_5)Y_R q\,. \tag{2.1}$$

Here q is a column vector representing the set of all quark fields, and $Y_{L,R}$ are matrices

$$Y_L = T_{3L} - 2\sin^2\theta Q\,, \tag{2.2}$$

$$Y_R = T_{3R} - 2\sin^2\theta Q\,, \tag{2.3}$$

where θ is the usual mixing angle, T_{3L} and T_{3R} are matrices representing the third component of weak SU(2) on the left- and right-handed quark fields, and Q is the charge matrix. We proceed to impose the condition of natural flavor conservation of neutral-current effects:

Condition I. We demand that the neutral current naturally conserves all quark flavors: strangeness, charm, etc.

In color gauge theories of the strong interactions, each of these quantities is simply the number of quarks of a given flavor; each quark flavor corresponds to a different eigenvalue of the quark mass matrix. Hence, we require that the matrices Y_L and Y_R be diagonal in the basis in which the quark mass matrix is also diagonal.

The mass term in the effective Lagrangian is of the form

$$-\bar{q}(1+\gamma_5)Mq - \bar{q}(1-\gamma_5)M^\dagger q\,, \tag{2.4}$$

where the mass matrix M need not be diagonal nor even Hermitian. M is in general arbitrary, but for the requirement that it conserve charge[3]: $[M,Q]=0$. We may diagonalize the mass matrix by defining new quark fields

$$q' = \tfrac{1}{2}(1+\gamma_5)U_L q + \tfrac{1}{2}(1-\gamma_5)U_R q\,, \tag{2.5}$$

with U_L and U_R unitary matrices acting on the flavor index of the quarks. In the new basis, the transformed mass matrix,

$$M' = U_L M U_R^{-1}\,, \tag{2.6}$$

is diagonal, and the matrices Y_L and Y_R are replaced by

$$Y_L' = U_L Y_L U_L^{-1}\,, \quad Y_R' = U_R Y_R U_R^{-1}\,. \tag{2.7}$$

Our condition requires that the neutral current conserve quark flavors in this basis, and hence that Y_L' and Y_R' be diagonal.

However, the demand of *natural* flavor conservation of the neutral currents requires that $Y_{L,R}'$ be diagonal whatever the choice of parameters in the theory, in particular, whatever the choice of M. Thus, U_L and U_R must be regarded as *arbitrary* unitary matrices which commute with Q. In order for $Y_{L,R}'$ to be diagonal for all such $U_{L,R}$, it follows that they must act on any set of quarks with the same charge as multiples of the unit matrix; they must in other words be functions of the matrix Q. It follows from Eqs. (2.2) and (2.3) that the same is true of the third component of SU(2):

$$T_{3L} = f_L(Q)\,, \quad T_{3R} = f_R(Q)\,. \tag{2.8}$$

That is, *all quarks with the same charge must have the same value of T_{3L} and the same value of T_{3R}*. This condition is clearly necessary and sufficient for the neutral currents (2.1) to conserve all quark flavors.

Condition II. We demand that the effective order αG neutral-current coupling induced by one-loop radiative corrections naturally conserve all quark flavors.

Consider the interaction of two fermions (quarks or leptons) without exchange of charge. The problem that concerns us here is whether one-loop diagrams could produce "dangerous" Fermi interactions of order αG_F, such as $(\bar{s}d)(\bar{s}d)$ (ruled out by the K_1^0-K_2^0 mass difference) or $(\bar{s}d)(\bar{\mu}\mu)$ (ruled out by the $K^0\to\mu^+\mu^-$ branching ratio). We are not concerned here with processes that result from the conversion of a virtual photon into a lepton pair, such as $K\to\mu^+\mu^-$.) We are now assuming that Condition I is satisfied, so that the neutral currents themselves conserve strangeness, charm, etc. In consequence, the only diagrams which could produce dangerous four-fermion interactions are those shown in Fig. 1. We will ignore all terms of order $\alpha G_F(m/m_W)^2$,

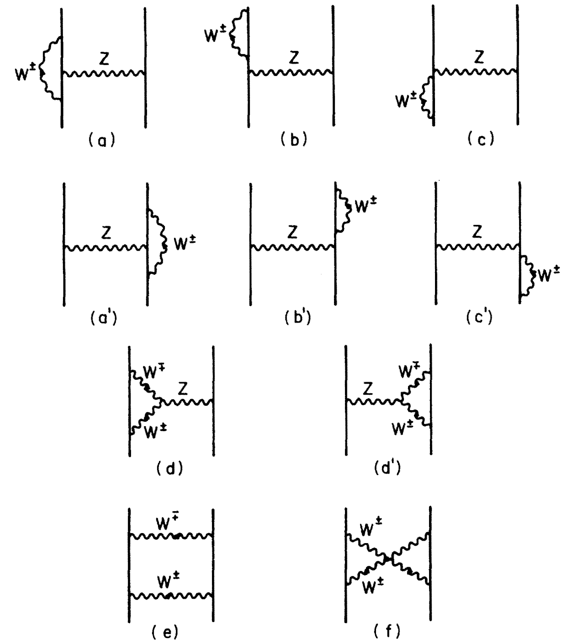

FIG. 1. Diagrams which can potentially produce strangeness-nonconserving (or charm-nonconserving) Fermi interactions of order αG_F. Here straight lines are quarks or leptons, and wavy lines are intermediate vector bosons. Each diagram must be summed over the two directions of flow for the W charges.

where m is a quark or lepton mass or momentum, so the calculations are fairly easy. (In particular, this justifies our neglect of one-loop graphs involving Higgs bosons.)

Diagram (a), together with the fermion-field-renormalization correction induced by diagrams (b) and (c), produces a change in the neutral-current coupling matrix Y in Eq. (2.1) proportional to

$$\Delta Y \propto T_+ Y T_- + T_- Y T_+ - \tfrac{1}{2}\{T_+, T_-\} Y - \tfrac{1}{2} Y \{T_+, T_-\}\,, \tag{2.9}$$

where $T_\pm$ are the matrices

$$T_\pm = T_1 \pm i T_2\,.$$

(A label L or R must be added everywhere, depending on the fermion helicity.) But $T_\pm$ raise or lower the values of Q and T_3, so

$$Y T_\pm = T_\pm (Y \pm a)\,, \quad a = 1 - 2\sin^2\theta$$

and therefore (2.8) gives

$$\begin{aligned}\Delta Y &\propto T_+ T_- (Y - a) + T_- T_+ (Y + a) - \{T_+, T_-\} Y \\ &= -a[T_+, T_-] = -2aT_3\,.\end{aligned} \tag{2.10}$$

Under Condition I, this automatically conserves strangeness, charm, etc. The same remarks apply to diagrams (a′), (b′), and (c′).

Diagrams (b), (c), (b′), and (c′) also require a fermion mass renormalization. However, this has no effect, because Condition I ensures that strangeness, charm, etc. are conserved for *all* possible charge-conserving quark mass matrices.

The two diagrams of type (d) together give a contribution proportional to $[T_+, T_-] = 2T_3$, so again Condition I ensures conservation of strangeness, charm, etc. The same applies to diagram (d′).

This leaves diagrams (e) and (f). These diagrams induce an effective Fermi interaction of the form

$$\xi \alpha G_F K_\mu K^\mu\,, \tag{2.11}$$

where ξ is a dimensionless number of order unity and K is an effective neutral current

$$\begin{aligned}K^\mu = \bar{q}\gamma^\mu(1+\gamma_5) Z_L q + \bar{q}\gamma^\mu(1-\gamma_5) Z_R q \\ + \text{lepton terms}\end{aligned} \tag{2.12}$$

where Z_L and Z_R are the matrices

$$Z_L = 3(\vec{T}_L^{\,2} - T_{3L}^{\,2}) + 10 T_{3L}\,, \tag{2.13}$$

$$Z_R = 3(\vec{T}_R^{\,2} - T_{3R}^{\,2}) - 10 T_{3R}\,. \tag{2.14}$$

As in the derivation of Condition I, we demand that Z_L and Z_R be diagonal in the basis in which the quark masses are diagonal, whatever the quark masses are. This implies that

$$\vec{T}_L^{\,2} = g_L(Q)\,, \quad \vec{T}_R^{\,2} = g_R(Q)\,.$$

That is, *all quarks with the same charge must have the same value of* $\vec{T}_L^{\,2}$ *and the same value of* $\vec{T}_R^{\,2}$. This condition is clearly both necessary and sufficient for the induced neutral current to conserve all quark flavors, given that Condition I is satisfied.

Let us see how these two conditions work in those SU(2) ⊗ U(1) theories with quark charges restricted to $\frac{2}{3}$ and $-\frac{1}{3}$. From Condition I we know that quarks of given charge and helicity must either all belong to singlets or all belong to doublets. Because left-handed weak currents are known to exist in nature, we conclude that all left-handed quarks must be in doublets. The right-handed quarks can be all singlets, as in the "standard" unified model,[2] or can be all doublets, as in the pure vector model.[4] Both models would then satisfy Conditions I and II. However, many other popular models do not. In particular, neither Condition I nor Condition II is satisfied by the six-quark model with doublet structure

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L \begin{pmatrix} t \\ b_\theta \end{pmatrix}_L \begin{pmatrix} u \\ b \end{pmatrix}_R .$$

Also, neither Condition I nor Condition II can ever be satisfied in SU(2) × U(1) models in which there are unequal numbers of charge $\frac{2}{3}$ and charge $-\frac{1}{3}$

quarks.

If we allow other values of quark charges, we may construct many other models satisfying our conditions. For example, we may suppose a model involving six quarks with the multiplet structure

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L (X)_L (Y)_L ,$$

$$\begin{pmatrix} d \\ X \end{pmatrix}_R \begin{pmatrix} s \\ Y \end{pmatrix}_R (u)_R (c)_R ,$$

involving new quarks X and Y which have charge $-\frac{4}{3}$. Both right-handed and left-handed quarks decompose into two doublets and two singlets, but with different charges. All quarks with the same charge and helicity have the same values for $\vec{T}^2$ and T^3, so Conditions I and II are satisfied here.

III. HIGGS-EXCHANGE NEUTRAL CURRENTS

There is a third condition for a natural absence of neutral-current flavor violation, having to do with the system of Higgs mesons. Renormalizable gauge theories of the weak and electromagnetic interactions generally involve physical scalar particles, widely known as Higgs mesons. If a neutral Higgs meson H has off-diagonal interactions such as $d+H \to s$, then its exchange can produce an effective $\Delta S = 2$ Fermi interaction

$$\bar{s} + d \to H \to s + \bar{d} . \tag{3.1}$$

The observed K_1^0-K_2^0 mass difference tells us that any such interaction must have a coupling strength G_H no greater than ~10^{-5} the usual Fermi coupling strength G_F.

How strong do we expect Higgs-exchange effects to be? The interaction of the Higgs field ϕ_i with the quarks will generally be of the form

$$-\bar{q}\Gamma_i(1+\gamma_5)q\phi_i - \bar{q}\Gamma_i^\dagger(1-\gamma_5)q\phi_i^\dagger , \tag{3.2}$$

where Γ_i is a matrix which acts on quark flavor indices. The quark mass matrix is then

$$M = M_0 + \Gamma_i \langle \phi_i \rangle , \tag{3.3}$$

where M_0 is a possible SU(2)$\otimes$U(1)-invariant bare mass, and $\langle\phi_i\rangle$ is the vacuum expectation value of ϕ_i. This shows that the typical value Γ of the coupling of a quark and a Higgs meson is of order

$$\Gamma \approx m_q / \langle \phi \rangle , \tag{3.4}$$

where m_q is a typical quark mass (or mass difference) and $\langle\phi\rangle$ is a typical vacuum expectation value. Also, the Higgs mass is of order

$$m_H \approx \sqrt{f}\, \langle \phi \rangle , \tag{3.5}$$

where f is a typical value of the ϕ^4 coupling constant. Hence the exchange of Higgs bosons produces an effective Fermi interaction with coupling of order

$$G_H \approx \Gamma^2/m_H^{\,2} \approx m_q^{\,2}/f\langle\phi\rangle^2 . \tag{3.6}$$

If we take $m_q \approx 1$ GeV and $\langle\phi\rangle \approx G_F^{-1/2} = 300$ GeV, then $G_H/G_F \approx 10^{-5}/f$. But as long as the scalar fields couple only weakly to themselves, we must have $f \ll 1$, so $G_H/G_F \gg 10^{-5}$. (Usually one assumes that f is of order α, in which case G_H/G_F is of order 10^{-3}.) We see that an off-diagonal Higgs coupling of the form $d \to H + S$ would be expected to produce much too large a K_1^0-K_2^0 mass difference. Thus we are led to our third condition.

Condition III. We demand that the coupling of each neutral Higgs meson be such as naturally to conserve all quark flavors: strangeness, charm, etc.

Because of our requirement of naturalness, the matrix M_0 must be regarded as an *arbitrary* SU(2)-invariant matrix commuting with Q. Similarly, the matrices Γ_i contain a number of *arbitrary* parameters equal to the number of SU(2)-invariant charge-conserving Yukawa couplings of the Higgs mesons to the quarks. For all such M_0 and for all such Γ_i the couplings of the neutral Higgs mesons must be diagonal in the basis in which M is diagonal.

Suppose that the set of quarks with given charge Q get their mass purely from a single neutral Higgs meson ϕ_Q^0. Then the mass matrix for these quarks of charge Q will be

$$M(Q) = \Gamma_Q \langle \phi_Q^0 \rangle \tag{3.7}$$

and Γ_Q is trivially diagonal in the basis which diagonalizes $M(Q)$. However, if there were more than one neutral Higgs boson contributing to the masses of quarks of a given charge, or if there were both an invariant mass term M_0 and a Higgs contribution, then there would be no reason to expect the couplings of the neutral Higgs bosons to conserve quark flavor. We conclude that Condition III is equivalent to the requirement that *quarks of given charge receive their mass either (1) through the couplings of precisely one neutral Higgs meson or (2) through an SU(2)-invariant mass term, but not by both mechanisms.* This condition might be evaded in special cases, as for instance through the judicious introduction of discrete symmetries. We have not explored these possibilities in detail.

In the standard model, the left-handed quarks are all doublets and the right-handed quarks are all singlets, so the Higgs bosons that couple to the quarks must all be doublets, and there can be no bare mass term M_0. The right-handed charge $+\frac{2}{3}$ quarks must couple to just one neutral Higgs boson

ϕ^0, a member of a doublet (ϕ^0, ϕ^-). Similarly, the right-handed charge $-\frac{1}{3}$ quarks must couple to just one neutral Higgs boson ϕ'^0, a member of a doublet (ϕ'^+, ϕ'^0). These two doublets may or may not be charge conjugates of each other. Condition III is then satisfied.

In the vector model, the left-handed and the right-handed quarks are all doublets, so the Higgs bosons that couple to the quarks must be singlets and/or triplets, and there can also now be an SU(2)-singlet bare mass term μ_0. The experimental values of the quark masses and mixing angles indicates that the quark mass matrix for each charge must have both SU(2)-singlet and SU(2)-triplet parts, so in this model it does not seem possible to eliminate the off-diagonal parts of the neutral-Higgs-boson couplings in a natural way. Condition III is not satisfied.

IV. MODELS WITH CHARM-CHANGING NEUTRAL CURRENTS

The result of the last two sections shows that unless we introduce exotic new quarks with charges of $\frac{5}{3}$ or $-\frac{4}{3}$, the only $SU(2) \otimes U(1)$ theories in which neutral-current effects naturally conserve strangeness and charm are the standard model and its generalization to any even number of quarks. It may involve at most two Higgs doublets (ϕ^0, ϕ^-) and $\phi'^+, \phi'^0)$ coupled to the quarks.

The vector model involves a neutral current which conserves charm and strangeness naturally, and this conservation law is respected by induced order-αG neutral-current effects. However, the absence of flavor violation mediated by neutral Higgs mesons cannot be imposed naturally (so far as we can see). Moreover, the vector model appears to be inconsistent with data on elastic[5] and deep-inelastic[6] neutrino-nuclear scattering, which show different neutrino and antineutrino cross sections.

The standard model may naturally satisfy our three conditions, but there are indications that it fails to describe certain data: The reported[7] "high-y anomaly" seems to require the presence of right-handed currents in the charged weak current which involve u and/or d quarks.[8] Of course, the present experimental situation must be regarded as tentative, but it is sufficiently disturbing so as to motivate a search for alternative theories.[9]

The reader will recognize that the three conditions of Secs. II and III result from the requirement that neutral-current effects naturally conserve *all* quark flavors. Yet, the neutral currents are known only to conserve strangeness. Nothing is known experimentally about whether or not they also conserve charm, let alone other proposed quark flavors. We are therefore free to suppose that the neutral currents naturally conserve strangeness and hence conserve all flavors of quarks with charge $-\frac{1}{3}$ but that they may violate the conservation of the other quark flavors, including charm.[10] By following the analysis of Sec. II, we see that the quarks of charge $-\frac{1}{3}$ must all have the same values of T_{3L}, $\vec{T}_L^{\,2}$, T_{3R}, and $\vec{T}_R^{\,2}$, but there is no restriction on the SU(2) transformation properties of quarks with other charges. Similarly, following the reasoning of Sec. III, there can be at most one neutral Higgs boson which couples to the charge $-\frac{1}{3}$ quarks, but any number of Higgs bosons which couple to other quarks.

To see how this can work in practice, consider a seven-quark model, with four quarks of charge $+\frac{2}{3}$ and three quarks of charge $-\frac{1}{3}$. To avoid a premature identification with quarks of definite mass, we will label the charge $+\frac{2}{3}$ quarks as P, C, L, A, and the charge $-\frac{1}{3}$ quarks as G, E, S. In order for strangeness to be conserved naturally, the left-handed G, E, S quarks must all be singlets or doublets, and likewise for the right-handed G, E, S quarks. Since the weak interactions certainly involve some left-handed quarks, the left-handed quarks must be grouped into three doublets and a singlet,

$$\begin{pmatrix} P \\ G \end{pmatrix}_L, \begin{pmatrix} C \\ E \end{pmatrix}_L, \begin{pmatrix} L \\ S \end{pmatrix}_L \text{ doublets}, \quad A_L \text{ singlet}. \tag{4.1}$$

The only remaining alternatives are that the right-handed quarks may be similarly grouped into three doublets and a singlet,

$$\begin{pmatrix} P \\ G \end{pmatrix}_R, \begin{pmatrix} C \\ E \end{pmatrix}_R, \begin{pmatrix} L \\ S \end{pmatrix}_R \text{ doublets}, \quad A_R \text{ singlet}, \tag{4.2}$$

or that they are all singlets. These correspond to modified versions of the standard and the vector models, respectively.

The seven-quark version of the standard model still has the problem of not containing right-handed currents which could account for the high-y anomaly. On the other hand, the seven-quark version of the vector model can now provide a neutral current with an axial-vector part that could produce different ν-N and $\bar{\nu}$-N cross sections, so let us restrict our attention to this case.[11]

We may define the quark states G, E, S to be just the charge $-\frac{1}{3}$ quarks d, s, b of definite mass. The quark states P, C, L, A are then defined by (4.1) and (4.2) in terms of their weak-interaction properties. Each of these is a linear combination of the charge $\frac{2}{3}$ quarks u, c, t, t' of definite mass, with the linear combinations in general different for the left- and right-handed quarks. In particular, if the coefficients of the u_L term in A_L and the u_R term in A_R are different, the weak neutral current will contain an axial-vector part involving u quarks.

The Higgs bosons which couple to quarks in the seven-quark version of the vector model may be SU(2) singlets, doublets, and/or triplets. However, according to the arguments of Sec. III, at most one neutral Higgs boson can couple to the charge $-\frac{1}{3}$ quarks G, E, S. The neutral member of a Higgs doublet (ϕ^0, ϕ^-) does not couple to the charge $-\frac{1}{3}$ quarks at all, so the Higgs fields that couple to the quarks in this theory can in general consist of one doublet (ϕ^0, ϕ^-) and either one singlet $\phi^{0\prime}$ (or a bare quark mass term M_0) or one triplet $(\phi'^+, \phi'^0, \phi'^{-1})$. This appears to be a rich enough set of Higgs fields to produce realistic quark masses and mixing angles, but we have not studied the problem in detail.

V. DO NEUTRAL-CURRENT INTERACTIONS CONSERVE CHARM?

Following the remarks of the preceding section, we now want to consider the experimental consequences of a theory in which the neutral currents themselves, or neutral-current effects induced by two-W or Higgs exchange, do not conserve charm.

We have seen that it is possible to construct an empirically adequate model in which Z^0 is coupled to a current with $\Delta C = 0$ and $\Delta C = \pm 1$ parts. This current can provide an additional mechanism for the production and decay of charmed particles, beyond the expected charged-current mechanism.

Charmed hadrons are ordinarily produced in high-energy neutrino-nucleon collisions by the charged-current couplings of either valence quarks,

$$\nu d \to \mu^- c\,, \tag{5.1}$$

or sea quarks,

$$\nu \to \mu^- c\bar{s}\,, \tag{5.2}$$

$$\bar{\nu} \to \mu^+ \bar{c} s\,. \tag{5.3}$$

If the neutral current is charm-changing, we may anticipate the additional valence processes

$$\nu u \to \nu c\,, \tag{5.4}$$

$$\bar{\nu} u \to \bar{\nu} c\,. \tag{5.5}$$

Events due to (5.4) or (5.5) in which the charmed hadron decays nonleptonically would resemble ordinary neutral-current events, except in that they involve an energy threshold (and a strange final state). Consequently, the existence of a charm-changing neutral current may lead to an observable rise in neutral-current cross sections above charm threshold.

Should a neutrino-produced charmed hadron decay semileptonically, mechanisms (5.1)–(5.3) would yield dilepton events. But (5.4) or (5.5) would yield a single charged lepton of relatively low energy. Events of this kind might be misinterpreted as ordinary charged-current events. However, there would be a very large loss of energy to the two unobserved neutrinos. Kinematically, these events would seem peculiar, and might even seem to lie outside the allowed region of the q^2-ν plot. Conceivably, events induced by (5.5) could account for at least part of the observed "high-y anomaly."

On the other hand, (5.4) and (5.5) probably must be weaker couplings than the conventional charged-current processes

$$\begin{aligned} \nu d &\to \mu^- u\,, \\ \nu u &\to \mu^+ d\,. \end{aligned} \tag{5.6}$$

This is because the charged-current semileptonic decay of a charmed hadron produced by (5.4) could yield a final state μ^+ while (5.5) could yield a final state μ^-. Such events would appear to violate conservation of lepton number, and no such violation has been reported.

Moreover, a charmed hadron produced by the conventional charged-current processes (5.1)–(5.3) could decay semileptonically, via the charm-changing neutral current, producing a charged lepton pair. Overall, this yields a trilepton event. Searches for neutrino-induced trileptons or soft wrong-charge single leptons could provide sensitive limits on the strength of a conjectured charm-changing neutral current. It would be ironic if charmed hadrons were observed to decay into final states including neutral lepton pairs: These are just the analogs of the strange-particle decays that charm was invented to suppress.

Thus far, we have considered possible violations of Condition I which give rise to charm-changing neutral-current effects of order G. If only Condition II or III is violated, these effects will be much smaller. Nevertheless, one or another of the virtual processes

$$u + \bar{c} \to \left\{ \begin{matrix} Z^0 \\ W^+ + W^- \\ \text{Higgs} \end{matrix} \right\} \to \bar{u} + c \tag{5.7}$$

will give rise to an effective $\Delta C = 2$ Fermi coupling. In any of these cases, there will be induced a mass splitting between the CP-even and CP-odd neutral charmed mesons D_1^0 and D_2^0 which is much larger than the D_1^0 or D_2^0 decay rates. Even if the direct decays induced by the charm-changing neutral current are very rare, the effects of the

D_1^0-D_2^0 mass splitting on the decays of neutral D's will be spectacular.

In those theories we are considering, the frequency of D-$\bar{D}$ transitions is large compared to the decay rate. *Thus, D^0 will be expected to decay into channels appropriate to $\bar{D}^0$ as often as not.* If there were no charm-changing neutral-current effects, the Cabibbo-favored decays of D^0 will be into $S=-1$ final states. If there are, D^0 will decay equally into $S=\pm 1$ final states. (The decay of D^0 into an $S=+1$ nonleptonic state is possible in the standard theory, but is doubly Cabibbo-suppressed, by the factor $\tan^4\theta \sim 2\times 10^{-3}$.)

Similar remarks apply to the charged-current semileptonic decays of D^0. Normally, such a decay produces a positively charged lepton. In the presence of charm-changing neutral-current effects, leptons of either sign are produced equally.

Let us consider the consequences of a large D_1^0-D_2^0 mixing on some experiments of current interest. Evidence for the associated production of new hadrons in e^+e^- annihilation has just been reported.[12] If these are interpreted in terms of charm, then the D^0 has been discovered at a mass of 1.865 GeV, in accordance with theoretical anticipation,[13] and has been observed to decay into $K\pi$ and $K\pi\pi\pi$. Two oppositely charmed particles must have been produced in association, possibly together with additional hadrons. One would expect a significant fraction of the weakly decaying charmed particles produced in e^+e^- annihilation to be D^0 and $\bar{D}^0$, perhaps the majority of them.[14] If the Glashow-Iliopoulos-Maiani mechanism *does* apply to charm as well as strangeness, we would expect that the final hadron state would have strangeness zero in the vast majority of cases. On the other hand, if there are charm-changing neutral-current effects, they will lead to complete $D^0\bar{D}^0$ mixing, and we expect $S=\pm 2$ final states to be almost as common as $S=0$ final states. *We are about to learn whether or not neutral currents conserve charm.*

Effects of D_1^0-D_2^0 mixing can also show up in neutrino experiments. Consider the production of charmed particles by high-energy neutrinos off sea quarks, for example

$$\nu p \to p + K^+ + D^0 + \mu^- . \qquad (5.8)$$

If D^0 decayed normally, we would end up with an $S=0$ final state most of the time. If D^0 decayed via $D^0\bar{D}^0$ mixing, $S=2$ would be as common for the final state as $S=0$. A *charm-changing* neutral-current coupling (either of order G, of order αG, or Higgs-mediated) reveals itself if charged-current $\Delta S=2$, $\Delta Q=2$ events are identified.

Neutrino-induced dimuon events have been detected at Fermilab.[15] About 100 events have been seen involving a final pair of oppositely charmed muons. These may be attributed to the effect of the conventional $\Delta C=\Delta Q$ part of the charged weak current. The incident neutrino has become the final μ^-, while the μ^+ is a decay product of a charmed hadron. Indeed, the observed kinematics favors this interpretation.[16] However, some of the time two μ^- are observed. These events *could* be attributed to the associated production of pairs of charmed hadrons by neutrinos, with one of them decaying semileptonically. This could yield all the $\mu^-\mu^-$ events and some of the $\mu^-\mu^+$ events. They could also be interpreted as "wrong" decays of D^0 which have been produced singly by neutrinos in reactions like (5.4). From the ratio of same-sign to opposite-sign dimuons, one could tell how often, among $\Delta C=1$ charged-current events, a D^0 is produced rather than any other $C=1$ weakly decaying hadron.

Finally, we consider the possibility that there is a significant associated production of charmed hadrons in deep-inelastic muon scattering. Semileptonic decays of the charmed particles would yield dilepton events and, more rarely, trilepton events. Without D_1^0-D_2^0 mixing, one would expect only the trimuon charge signature $\mu^\pm\mu^+\mu^-$, depending on whether the incident beam is μ^+ or μ^-. This is because the $C=1$ hadron normally produces only a positive lepton, and a $C=-1$ hadron normally produces only a negative lepton. If there is D_1^0-D_2^0 mixing, we anticipate as well the charge signatures $\mu^\pm\mu^+\mu^+$ and $\mu^\pm\mu^-\mu^-$.

It is evidently important experimentally to learn whether or not the Glashow-Iliopoulos-Maiani mechanism extends naturally to charm, and we have sketched a few experimental ramifications. It is also important to know if neutral-current effects are charm-conserving for theoretical reasons—as a guide to the development of a complete theory of weak interactions.

Note added in proof. The problems treated here have been discussed recently from a rather different point of view by E. A. Pachos [Phys. Rev. D 15, 1966 (1977)] and by K. Kang and J. E. Kim [Phys. Lett. 64B, 93 (1976)].

ACKNOWLEDGMENT

We wish to thank M. Barnett, A. De Rújula, H. Georgi, and B. W. Lee for helpful discussions.

*Work supported in part by the National Science Foundation under Grant No. MPS75-20427.

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