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Changing the Charmed Current*

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We propose as an addition to the conventional charm-changing charged current the $V+A$ current $\bar{\mathcal{P}}'\gamma_\mu(1-\gamma_5)\mathcal{N}$. It explains the observed enhancement of nonleptonic $\Delta I=\frac{1}{2}$ weak decays, allows low-lying charmed hadrons to decay comparably into strange and nonstrange final states, predicts the appearance of $\mu^- l^-$ (as well as $\mu^- l^+$) dilepton events in neutrino interactions, and leads to copious quasielastic charm production by neutrinos.

A popular picture of particle physics has as fundamental fermions four kinds of quark color triplets and the known leptons.[1] Strong interactions are an exact color SU(3) gauge theory[2]; weak interactions and electromagnetism are a spontaneously broken SU(2)$\otimes$U(1) gauge theory.[3] Three kinds of quarks ($\mathcal{P}$, $\mathcal{N}$, λ) make up observed hadrons; the fourth charmed quark $\mathcal{P}'$ is needed to explain the observed absence of strangeness-changing neutral-current phenomena[4] in order G and αG, and leads to the existence of charmed hadrons. The charged weak current is usually assumed to be

$$J_\mu=\bar{\mathcal{P}}\gamma_\mu(1+\gamma_5)(\mathcal{N}\cos\theta+\lambda\sin\theta)+\bar{\mathcal{P}}'\gamma_\mu(1+\gamma_5)(\lambda\cos\theta-\mathcal{N}\sin\theta)+\bar{\nu}\gamma_\mu(1+\gamma_5)e+\bar{\nu}'\gamma_\mu(1+\gamma_5)\mu. \quad (1)$$

In this paper we suggest an alternative choice for this current, and explore its consequences.

The usual weak current, Eq. (1), corresponds to a generator of weak SU(2), leads to a neutral current conserving charm and strangeness, and reproduces the observed phenomenology of leptonic and semileptonic weak decays. But it does not give an adequate description of strangeness-changing nonleptonic decays:

(I) *No satisfactory explanation has been found for the nonleptonic* $\Delta I=\frac{1}{2}$ *rule.* Arguments based on current algebra[5] or on asymptotic freedom[6] simply do not explain why $\Delta I=\frac{1}{2}$ amplitudes are generally more than 20 times larger than $\Delta I=\frac{3}{2}$ amplitudes.

(II) *No satisfactory explanation has been found for the anomalous strength of nonleptonic decays.* Both the decay modes $\Lambda\to p\pi^-$ and $\Lambda\to pe\bar{\nu}$ proceed through couplings of the same intrinsic strength, yet the nonleptonic process is hundreds of times faster than the β process. This is characteristic of all $\Delta I=\frac{1}{2}$ decay modes. On the other hand, the $\Delta I=\frac{3}{2}$ decay $K^+\to\pi^+\pi^0$ proceeds at a rate comparable with semileptonic decays.

We propose the simultaneous solution to both of these problems. We do not depend on any conjectured "dynamical enhancement" of the $\Delta I=\frac{1}{2}$ part of the conventional effective Lagrangian. We modify the charged weak current, remaining in the context of an SU(2)$\otimes$U(1) gauge theory, so as to produce an additional contribution to the nonleptonic effective Lagrangian which is $\Delta I=\frac{1}{2}$ and dominant. Leptonic, semileptonic, and $\Delta I=\frac{3}{2}$ nonleptonic interactions are not affected.

We choose, as an alternative to the conventional charged weak current,[7]

$$J_\mu'=J_\mu+\bar{\mathcal{P}}'\gamma_\mu(1-\gamma_5)\mathcal{N}. \quad (2)$$

Like J_μ, the new current corresponds to a generator of weak SU(2). This time, the right handed $\mathcal{P}'$ and $\mathfrak{N}$ transform as a weak doublet rather than as singlets. It leads to a neutral current conserving charm and strangeness, and reproduces known leptonic and semileptonic phenomenology. *The new current differs from the old only in the couplings of the charmed quark.* These additional couplings are $V+A$ rather than $V-A$. They do not undo the suppression of neutral lepton currents and $\Delta S=2$ in order G and αG, that was the *raison d'être* for charm.

Consequences for nonleptonic decays of hyperons and kaons.—With the current of Eq. (2) there are two contributions to nonleptonic $\Delta S=\pm 1$ decays. The conventional contribution involves only the current J^μ. It is proportional to $\sin\theta\cos\theta$ and contains both $\Delta I=\frac{1}{2}$ and $\frac{3}{2}$. In our model there is an additional contribution involving the new right-handed current. It yields a term in the $\lambda, \mathfrak{N}$ mass operator from a diagram in which an $\mathfrak{N}$ quark emits a W, becoming a $\mathcal{P}'$ quark which reabsorbs the W and becomes a λ quark. After mass and wave-function renormalization, the finite and momentum-dependent remainder is of order G and is obviously $\Delta I=\frac{1}{2}$. It is proportional to $\cos\theta$, not to $\sin\theta\cos\theta$, and because it arises from an interplay between $V-A$ and $V+A$ couplings, it is proportional to $m_{\mathcal{P}'}$. Thus, $\Delta I=\frac{1}{2}$ nonleptonic processes are enhanced relative to $\Delta Y=1$ semileptonic processes *both* because of the large mass of the $\mathcal{P}'$ quark and because of the absence of Cabibbo suppression. Nonleptonic $\Delta I=\frac{3}{2}$ decays, like $K^+\to\pi^+\pi^0$, involve only the conventional current and are comparable in strength to $\Delta Y=1$ semileptonic processes.

The successful predictions of current algebra are left intact. For semileptonic decays, the relevant currents remain as they are in conventional theories. For nonleptonic decays, the dominant ($\Delta I=\frac{1}{2}$) contribution to the effective Lagrangian is "chirally pure" because it involves only the right-handed combination $(1-\gamma_5)\mathfrak{N}$. Commutation with the chiral SU(2) generator $Q_5^{(i)}$ is equivalent to commutation with $Q^{(i)}$. Thus, the slopes and decay rates for $K\to 3\pi$ may be computed from the single parameter describing $K\to 2\pi$ ($\Delta I=\frac{1}{2}$). Similarly, the deduction of the S-wave Lee-Sugawara relation from current algebra is unaffected.[5]

Quasielastic production of charmed baryons by neutrinos.—In the conventional theory, quasielastic production of a single charmed baryon is forbidden for incident $\bar\nu$, but allowed via the $\sin\theta$ coupling for ν. Above charm threshold, several percent of the ν events should be quasielastic production. In our model, quasielastic production is still forbidden for $\bar\nu$, but proceeds for ν through the new $V+A$ couplings, unsuppressed by $\sin\theta$. *Above charm threshold, quasielastic charm production should account for a sizable fraction of all events.*

The following quasielastic processes proceed via the new $V+A$ couplings and are not suppressed by $\sin^2\theta$:

$$\nu p\to\begin{cases}\mu^-\Sigma_c^{++},\\ \mu^-\Sigma_c^{*++},\end{cases}$$

$$\nu n\to\begin{cases}\mu^-\Sigma_c^{+},\\ \mu^-\Sigma_c^{*+},\\ \mu^-\Lambda_c^{+},\end{cases}$$

where Λ_c, Σ_c, and Σ_c^* are the charmed analogs to Λ, Σ, and $\Sigma^*(1385)$. One such event has been reported.[8] The quasielastic production of charmed hadrons should differ significantly from ordinary quasielastic scattering. It should not be so rapidly decreasing as a function of q^2, the momentum transfer. This is because the form factors of charm-changing currents should depend on the charmed vector-meson mass[1] (~ 2 GeV) rather than on the ρ or K^* mass.

Deep inelastic ν and $\bar\nu$ scattering.—Well above charm threshold the additional current leads to a $(1-y)^2$ component in the scattering of ν's off valence $\mathfrak{N}$ quarks.[9] Characteristic threshold effects in x and y distributions have been discussed in detail. (In Ref. 9, see the analysis of the fancy model where $\mathfrak{N}_R$ has weak isospin $\tau_{\mathfrak{N}}=-\frac{1}{2}$.) This contribution to scattering off valence quarks would cause the ratio R of $\bar\nu$ to ν total cross sections to change from $R=\frac{1}{3}$ below charm threshold to $R=\frac{1}{4}$ well above.[9] On the other hand, scattering off quarks and antiquarks in the "sea" probably contributes equally to ν and $\bar\nu$ scattering (but not to quasielastic scattering), and tends to increase the value of R.

Decays of charmed particles.—In the conventional theory, the favored decay schemes of charmed particles satisfy the selection rule $\Delta C=\Delta S=\pm 1$, and low-lying charmed particles preferentially decay into strange final states. Other channels are suppressed by $\tan^2\theta$ in rate. This is not the case in our new model, where $\Delta C=\Delta S=\pm 1$ and $\Delta C=\pm 1$, $\Delta S=0$ decays complete on equal terms. *We expect comparable numbers of strange and nonstrange final states in the decays of singly charmed nonstrange hadrons.*

In contrast to the situation for strange-particle decays, there is no important enhancement of nonleptonic relative to semileptonic decay. Neither mode is suppressed relative to the other by $\sin^2\theta$, nor enhanced by the large $\mathcal{P}'$ mass. We anticipate sizable branching ratios into semileptonic channels, both strange and nonstrange. For example, the $J^P = \frac{1}{2}^+$ $(\mathcal{P}'\mathcal{P}\mathfrak{N})^+$ state analogous to Λ would be expected to have comparable branching ratios into such modes as $\Lambda\pi^+$, $N\pi^+$, $\Lambda l^+\nu$, and $Nl^+\nu$.

"Wrong" dileptons.—In ν scattering oppositely charged dilepton events may be observed by the production of a charmed hadron C with subsequent (fast) semileptonic decay

$$\nu_\mu N \to \mu^- C + \ldots, \quad C \to l^+\nu + \ldots.$$

Such events were predicted[10] and observed.[11] However, it is also possible to observe dilepton events involving $\mu^-\mu^-$ or μ^-e^- due to the "wrong" decay of the $J^P = 0^-$ $D = (\mathcal{P}\mathcal{P}')$ state:

$$\nu_\mu N \to \mu^- D + \ldots, \quad D \to l^-\nu^- + \ldots.$$

In the conventional theory, both D and $\bar{D}$ may decay into the same $Y=0$ channels with amplitudes suppressed by $\sin^2\theta$. This can lead to a difference in lifetime and in mass between $D_1 = (\bar{\mathcal{P}}\mathcal{P}' + \bar{\mathcal{P}}'\mathcal{P})$ and $D_2 = (\bar{\mathcal{P}}\mathcal{P}' - \bar{\mathcal{P}}'\mathcal{P})$, and consequently, to the decay of D into the "wrong" lepton. However, one obtains[12]

$$\frac{\Gamma(D \to \mu^-\bar{\nu} \ldots)}{\Gamma(D \to \mu^+\nu \ldots)} \sim \tan^4\theta \sim 10^{-3}.$$

In our modified theory, there is no Cabibbo suppression of the common decay modes of D and $\bar{D}$. Thus, the difference in mass and decay rate of D_1 and D_2 could be comparable to their decay rates. "Wrong" semileptonic decays of D could have a branching ratio similar to (but smaller than) its normal semileptonic decays. Reported[13] experimental evidence of "wrong" dileptons signifies D production in our modified scheme. Of the final states containing μ^-l^-, we expect roughly $\frac{1}{4}$ to contain *two strange particles with the same strangeness,* as in the following process:

$$\nu + p \to \mu^- + p + K^+ + D, \quad D \to \mu^- + \bar{\nu} + K^+.$$

Nonleptonic "wrong" decays of the D can lead to doubly strange final states with a single μ^-: *apparent $\Delta S = 2$ events.* Similar comments about $\mu^+\mu^+$ or μ^+e^+ dilepton events can of course be made for $\bar{\nu}$ scattering.

Neutral currents.—The theory as it stands is not renormalizable. The cancelation of anomalies discovered by Bouchiat, Iliopoulos, and Meyer[14] has been upset. Further modifications of the theory involving extra quarks or extra leptons are necessary to eliminate the anomalies. The properties of the neutral currents will depend on just what modifications are made.[9] This subject will be discussed in detail elsewhere.

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Measurement of Prompt-Muon Production in Nucleon-Nucleus Collisions*

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We have measured the production cross section for prompt muons relative to pions, produced in nucleon-nucleus interactions at incident energies from 30 to 300 GeV and for muon transverse momenta from 1 to 2.3 GeV/c. Upper limits on the production and leptonic decay of heavy particles are presented.

Several experiments have recently reported evidence for prompt-lepton production in nucleon-nucleus collisions.[1-5] Since the cross section appears to be substantially larger than estimates based on known mechanisms, it is particularly important to map out the features of this new phenomenon.

We report here a measurement of prompt-muon production in nucleon-carbon collisions over the range of incident proton energies from 30 to 300 GeV and for muon transverse momenta from 1.0 to 2.3 GeV/c.[6] The experiment was performed at the Fermilab. A detailed description of the apparatus has already been given.[7] Briefly, the detector consisted of a magnetic spectrometer equipped with eight proportional chamber planes and located at 91 mrad with respect to the accelerator's internal beam. A 21-absorption-length hadron shield was positioned between the production target and spectrometer. The first element of the absorber was a 38-cm-long Heavimet (tungsten) block beginning 5.1 cm downstream from the target. This block was located 2.1 cm below the proton beam. The rest of the absorber consisted of iron blocks located 3.5 cm below the beam. The first few elements of this shield could be withdrawn remotely to permit a measurement of the muon rate in the spectrometer as a function of the distance available for hadron decay between the target and shield. This distance was varied hourly during the experiment, as was the field polarity of the magnet. A single setting of the spectrometer's magnetic field allowed a measurement of muon momenta above 9 GeV/c for both charges simultaneously. A pair of lead-glass Cherenkov counters at the downstream end of the apparatus was used to verify that hadron contamination of the data was less than 2%, as expected behind the thick shield.

Figure 1 shows the observed muon momentum spectrum for a sample of the data taken with the longest decay path used in the experiment, 110 cm. The shape is fully consistent with that expected for muons from pion and kaon decay. The predicted spectrum was calculated from measured production cross sections[8] combined with