the $[s_0/(s_0-t)]^{\alpha+1}$ factor in Eq. (2). However, while the statistical significance is not overwhelming, Figs. 3 and 4 do show that the data for $M^2 \gtrsim 20$ GeV^2 at high $|t|$ (i.e., $|t| \gtrsim 0.5$ GeV^2) are consistently above the model predictions. This suggests that other than pion exchange may contribute appreciably in this not-very-peripheral region. Further high-statistics data at the higher t values would be desirable.

IV. CONCLUSIONS

We have shown that the average charged multiplicity data for the reaction $\pi^- p \rightarrow pX$ at 205 GeV/c can be reasonably understood with a simple version of the multiperipheral model for $20 \lesssim M^2 \lesssim 200$ GeV^2 and $|t| \lesssim 1$ GeV^2. It would clearly be of interest to extend the present multiperipheral analysis to higher values of s, M^2, and $|t|$; to the higher multiplicity moments of X, such as f_2 and f_3; and to other reactions of the form $a + p \rightarrow pX$.

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Structure of the hadronic neutral current

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On the basis of general phenomenological arguments, it is suggested that the neutral weak hadronic current should transform as a U-spin scalar. Possible tests for this hypothesis are proposed, and the implication of the available data is discussed. The question whether such a structure can be generated from unified gauge theories is also examined.

Several recent experiments[1-5] have established the existence of neutral currents in neutrino-induced reactions. Qualitatively at least, such neutral currents have been proposed in some gauge-theory models of weak and electromagnetic interactions. Not surprisingly, a great deal of effort has been directed recently at testing the original Weinberg-Salam model,[6] and although nothing conclusive can be said at the present time, more definitive and elaborate comparisons will undoubtedly be forthcoming as the experimental data grow.

At this stage, however, it is worthwhile to keep an open mind on various theoretical or phenomenological possibilities. Even within the context of unified gauge theories such an attitude is useful, due to the fact that several models exist or can be constructed with different structures for neutral currents, although probably none is as simple in appeal (at least for the leptonic sector) as the original Weinberg-Salam model.

In this note we propose a general structure for the weak hadronic neutral current from a phenomenological point of view. This structure is a generalization of a recent proposal due to Sakurai.[7] We suggest possible tests for this current structure, and also discuss the implications of the available data. The question whether such structures for neutral currents can be generated from gauge theories is also examined.

The neutral hadronic currents must satisfy some stringent restrictions. Experimental data[8] on $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, etc. strongly suggest that the strangeness-changing piece from hadronic neutral currents must be highly suppressed or absent. For the charged currents, on the other hand, one obviously needs strangeness-changing currents obtainable by the Cabibbo prescription of rotating the charge-raising and charge-lowering currents $(V+A)_\mu^{1\pm i2}$ around the seventh axis in SU(3) space. If the Cabibbo prescription is generalized, so that we demand that not only the strangeness structure of the charged currents but also that of the neutral current be obtained by Cabibbo rotation, it is easy to see that a simple way to avoid neutral strangeness-changing currents is to require that the neutral current be invariant under this rotation. Accordingly we propose that the neutral hadronic current should transform as a U-spin scalar.

We shall assume that the neutral current contains only vector and axial-vector pieces, although in principle other covariant structures are possible. It is natural to consider the octets of vector and axial-vector currents belonging to the chiral $\mathrm{SU}_L(3)\otimes\mathrm{SU}_R(3)$ group, so that the only U-spin-invariant structure is given by $J_\mu^3 + (1/\sqrt{3})J_\mu^8$, where J_μ is a vector (V_μ) or an axial-vector (A_μ) current. In this case, then, the requirement that the neutral current be a U-spin scalar leads to the following structure for the neutral hadronic current:

$$\mathcal{J}_\mu^{(0)} = a\left(V_\mu^3 + \frac{1}{\sqrt{3}}V_\mu^8\right) + b\left(A_\mu^3 + \frac{1}{\sqrt{3}}A_\mu^8\right). \tag{1}$$

It is clear that we can always add contributions from possible SU(3)-singlet vector or axial-vector currents, so that a general U-spin-invariant structure can be written as

$$\mathcal{J}_\mu^{(0)} = a\left(V_\mu^3 + \frac{1}{\sqrt{3}}V_\mu^8\right) + b\left(A_\mu^3 + \frac{1}{\sqrt{3}}A_\mu^8\right) + (cV_\mu + dA_\mu)_{\mathrm{SU(3)\ singlet}}. \tag{2}$$

We see that simple phenomenological considerations[9] based on the absence of strangeness-changing neutral currents lead to the U-spin-invariant structures (1) or (2) for the neutral hadronic current.

The hypothesis that the neutral hadronic current is a U-spin scalar can in principle be tested by future experiments. In analogy to photoproduction,[10] it is easy to check that the following relations for the production of decuplet states in neutrino scattering must be satisfied, if U-spin invariance is assumed:

$$\begin{aligned}
&\sigma(\nu p\to\nu\Delta^0X)+\sigma(\nu p\to\nu\Xi^{*0}X)=2\sigma(\nu p\to\nu Y_0^*X),\\
&\sigma(\nu p\to\nu\Omega^-X)-\sigma(\nu p\to\nu\Xi^{*-}X)\\
&\qquad=\sigma(\nu p\to\nu\Xi^{*-}X)-\sigma(\nu p\to\nu Y^{*-}X)\\
&\qquad=\sigma(\nu p\to\nu Y^{*-}X)-\sigma(\nu p\to\nu\Delta^-X),\\
&3\sigma(\nu n\to\nu Y^{*-}X)+\sigma(\nu n\to\nu\Delta^-X)\\
&\qquad=3\sigma(\nu n\to\nu\Xi^{*-}X)+\sigma(\nu n\to\nu\Delta^-X),
\end{aligned} \tag{3}$$

where X stands for the sum over all hadronic states. Also, for the meson and baryon octets, the following triangular inequalities for the exclusive reactions must be satisfied:

$$\begin{aligned}
&[2\sigma(\nu p\to\nu\pi^+n)]^{1/2}\\
&\qquad\le[3\sigma(\nu p\to\nu K^+\Lambda)]^{1/2}+[\sigma(\nu p\to\nu K^+\Sigma^0)]^{1/2},\\
&[\sigma(\nu p\to\nu\pi^0p)]^{1/2}\\
&\qquad\le[2\sigma(\nu p\to\nu K^0\Sigma^+)]^{1/2}+[3\sigma(\nu p\to\nu\eta p)]^{1/2}.
\end{aligned} \tag{4}$$

Note that the relations (3) and (4) are also valid if we replace ν by $\bar{\nu}$. We might also mention that the assumption that $\mathcal{J}_\mu^{(0)}$ does not contain an $I=2$ piece can also be tested[11] in principle. For example, the absence of an $I=2$ piece would imply that

$$\begin{aligned}
&3\sigma(\nu d\to\nu\Delta^+X)+\sigma(\nu d\to\nu\Delta^-X)\\
&\qquad=3\sigma(\nu d\to\nu\Delta^0X)+\sigma(\nu d\to\nu\Delta^{++}X)\\
&[\sigma(\nu d\to\nu pp\pi^-)]^{1/2}\\
&\qquad\le2[\sigma(\nu d\to\nu pn\pi^0)]^{1/2}+[\sigma(\nu d\to\nu nn\pi^+)]^{1/2}.
\end{aligned} \tag{5}$$

Several other tests for the U- and I-spin structure of the neutral current can be written down in analogy with the photoproduction relations discussed in Refs. (10) and (11).

From a theoretical point of view, one may inquire if structures like (1) and (2) can be generated from a renormalizable gauge theory. For this purpose, it is usual to consider the SU(2) gauge group generated by the charges $Q^\pm$ corresponding to the charged currents, and $Q^{(0)}$ corresponding to the neutral current. However, if $Q^\pm$ are given by the usual Cabibbo form

$$Q^\pm = \cos\theta(F+F_5)^{1\pm i2} + \sin\theta(F+F_5)^{4\pm i5},$$

where F^i and F_5^i are the standard $\mathrm{SU(3)}\otimes\mathrm{SU(3)}$ generators, it follows that $Q^{(0)}=\frac{1}{2}[Q^+,Q^-]$ will contain a strangeness-changing piece. Unfortunately no simple solution has been found for this problem. Usually one employs the GIM construction,[12] where the weak hadronic currents are written in terms of suitable vector and axial-vector currents built out of four quarks, the familiar $\mathcal{P}$, $\mathfrak{N}$, and λ and the charm-carrying quark $\mathcal{P}'$. In particular, for the purely weak sector of the Weinberg-Salam model,[6] i.e., for weak interactions invariant under the gauge group $SU_L(2)$, the GIM construction gives[13]

$$\mathcal{J}_\mu^{(0)}=\left(V_\mu^3+\frac{1}{\sqrt{3}}V_\mu^8-(\tfrac{2}{3})^{1/2}V_\mu^{15}\right)+(V_\mu\to A_\mu)\,, \tag{6}$$

where $V_\mu^\alpha=i\bar{q}\gamma_\mu(\lambda^\alpha/2)q$ and $A_\mu^\alpha=i\bar{q}\gamma_\mu\gamma_5(\lambda^\alpha/2)q$. Here q is a column matrix with the quark states $\mathcal{P}$, $\mathfrak{N}$, λ, and $\mathcal{P}'$, and λ^α ($\alpha=1,2,\ldots,15$) are 4×4 matrices[13] which are generalizations of the more familiar λ matrices of the SU(3) theory. Note that (6) is a U-spin scalar and is in fact a special case of the structure (2). Unification of weak and electromagnetic interactions can be achieved by extending the gauge group to $SU_L(2)\otimes Y_L$ in the well-known manner, so that the neutral current that couples to the neutral weak boson Z_μ is then given by $\mathcal{J}_\mu^{(0)}-2\sin^2\theta_W J_\mu^{\text{em}}$, also a U-spin scalar (θ_W is the Weinberg angle[6]), with a structure again like (2).

Alternatively, one can consider the colored-quark model where the usual quarks, $\mathcal{P}$, $\mathfrak{N}$, and λ come in three different colors. Several gauge theories incorporating the colored quarks can be constructed. In the Bég-Zee version,[14] the neutral current, coupled to Z_μ, for the familiar hadrons (neutral with respect to color) is given by just the electromagnetic current

$$\mathcal{J}_\mu^{(0)}=J_\mu^{\text{em}}\,, \tag{7}$$

which is a special case of the current (1) for the usual hadronic structure of the electromagnetic current. It is clear from these examples that gauge theories can in fact generate the U-spin-invariant structures (1) or (2) for the neutral currents. The specific values of the constants $a,\ldots,d$ of course depend on the details of the model or its variants. However, the phenomenological structure (1) or (2) is clearly more general than any specific gauge-theory result, and by itself merits experimental confrontation.

Sakurai has recently proposed that the weak hadronic neutral current be identified with the SU(3)-singlet baryon current (vector and possibly axial-vector). As emphasized by him, such a current would be invariant under the Cabibbo rotation. In fact his current is a special case of (2) with $a=b=d=0$. Sakurai has not made any attempt at constructing a unified gauge theory model that would reproduce such a neutral current. However, such models can be constructed. As an example we discuss a rather trivial extension of the Georgi-Glashow model.[15] The Georgi-Glashow model is based on the SO(3) gauge group, generated by the weak charges $Q^\pm$ and the electromagnetic charge Q, and contains no weak neutral currents. Consider now the total fermion neutral current, the conserved charge Q_F, corresponding to which is the sum of the baryon and lepton numbers. Note that Q_F generates the Abelian fermion gauge group $U_F(1)$, and since Q_F commutes with $Q^\pm$ and Q we may consider the extended gauge group $SO(3)\otimes U_F(1)$. In contrast with the SO(3) gauge symmetry, which is spontaneously broken by the Higgs mechanism to generate masses for the charged vector bosons (leaving the photon massless), we may realize the Abelian gauge symmetry $U_F(1)$ by introducing, to start with, a massive gluon coupled to the absolutely conserved fermion current of a pure vector type. Since a massive gluon theory is renormalizable, we have a renormalizable $SO(3)\otimes U_F(1)$ gauge theory model which reproduces Sakurai's vector baryon current as the weak hadronic neutral current. Obviously, one can adjoin[16] $U_F(1)$ (or for that matter other Abelian gauge groups generated, for example, by conserved quantities like charm, etc.) to any renormalizable theory based on a gauge G, as long as $U_F(1)$ commutes with G. Especially, this allows us to add a unitary singlet hadronic vector current to any spontaneously broken gauge-theory model, such as the Weinberg-Salam model, the Georgi-Glashow model, the Bég-Zee model, etc. These are simple examples of the so-called mixed renormalizable gauge theories.[17]

Undoubtedly, as more experimental information becomes available, it will be possible to test the structures (1) and (2) for the neutral currents. The choice between (1) and (2) is also related to the question whether the hadronic part of the electromagnetic current contains a pure SU(3) singlet component or not. Although it is not essential, we shall assume here for the sake of simplicity the validity of (1) as well the absence of any SU(3) singlet component in the electromagnetic current. Then the semileptonic interaction between neutrinos and hadrons, at momentum transfers not too high, will be described by the effective coupling[18]

$$\begin{aligned}\mathcal{L}_{\text{int}}=&\,i\frac{G_V}{\sqrt{2}}\bar{\nu}\gamma_\lambda(1+\gamma_5)\nu\left(V_\lambda^3+\frac{1}{\sqrt{3}}V_\lambda^8\right)\\&+i\frac{G_A}{\sqrt{2}}\bar{\nu}\gamma_\lambda(1+\gamma_5)\nu\left(A_\lambda^3+\frac{1}{\sqrt{3}}A_\lambda^8\right).\end{aligned} \tag{8}$$

We can also add contributions from the electron and the muon to the neutral currents, if we wish, in analogy to the electromagnetic interaction. The interaction (8) leads to an inequality

$$\frac{d}{dt}\sigma(\nu T\to\nu X)+\frac{d}{dt}\sigma(\bar{\nu}T\to\bar{\nu}X)\geq\frac{G_V{}^2}{4\pi^2\alpha^2}t^2\frac{d}{dt}\sigma(eT\to eX) \tag{9}$$

for any unpolarized target T and for any inclusive or exclusive final state X, in a one-photon exchange approximation for the electromagnetic process $eT \to eX$. In Eq. (9), α is the fine-structure constant and t is the square of the momentum transfer four-vector between leptons. This inequality enables us to estimate an upper bound for G_V. For this purpose, we adapt the calculations of an earlier publication[19] and find that the available data on the deep-inelastic neutrino and electron scattering cross sections imply

$$G_V \leq G_F\,, \tag{10}$$

where G_F is the usual Fermi coupling constant.

Actually, a more precise relation can be written down, if we assume that for the deep-inelastic region chiral $U_L(2) \otimes U_R(2)$ or $SU_L(3) \otimes SU_R(3)$ symmetry will become asymptotically[20] valid. With this assumption, the vector and axial-vector current contributions will become equal, so that in the deep-inelastic region, we now expect the equality

$$\frac{d}{dt}\sigma(\nu T \to \nu X) + \frac{d}{dt}\sigma(\bar{\nu} T \to \bar{\nu} X) = \frac{1}{4\pi^2\alpha^2}(G_V{}^2 + G_A{}^2)t^2 \frac{d}{dt}\sigma(eT \to eX)\,. \tag{11}$$

The present experimental data are consistent[19] with

$$G_V{}^2 + G_A{}^2 \simeq G_F{}^2\,, \tag{12}$$

which makes it tempting to set

$$G_V = G_F \cos\phi\,, \quad G_A = G_F \sin\phi \tag{13}$$

in terms of a new angle ϕ.

The natural choice would be to assume $\phi = \pi/4$ corresponding to the $V-A$ combination in (8). However, recent experiments[4] at FNAL seem to suggest that

$$\sigma(\nu_\mu + N \to \nu_\mu + \text{anything}) \simeq \sigma(\bar{\nu}_\mu + N \to \bar{\nu}_\mu + \text{anything})\,. \tag{14}$$

If the equality (14) is confirmed it will imply the absence of the VA interference term, so that either $G_A = 0$ or $G_V = 0$. Although there is no *a priori* reason for choosing one or the other of the two possibilities, we shall in the rest of the paper set $G_A = 0$ or $\phi = 0$. In this choice, we are motivated by the following considerations. Since $V_\lambda^3 + (1/\sqrt{3})V_\lambda^8$ is the usual hadronic electromagnetic current, and since for a two-component neutrino $\bar{\nu}\gamma_\lambda(1+\gamma_5)\nu = 2\bar{\nu}\gamma_\lambda\nu$, the G_V term in Eq. (8) admits of an attractive physical interpretation. It effectively represents an electromagnetic interaction[19] between the neutrinos and the hadrons, through a one-photon exchange, where the photon couples to the neutrino through its charge radius. This interpretation implies

$$\frac{G_V}{\sqrt{2}} = \frac{\pi}{3}\alpha a^2 \tag{15}$$

in the approximation $F_1^{(\nu)}(t) \simeq \frac{1}{6}a^2 t$ for the neutrino electromagnetic form factor, where a^2 = mean square charge radius of the neutrino. Furthermore, irrespectively of this interpretation, one can construct gauge theories, like the Bég-Zee model,[14] which reproduce the electromagnetic current as the only contribution to the neutral weak hadronic current for the usual hadrons. Another alternative but rather speculative interpretation is the conjecture that the vector interaction may have something to do with the neutrino theory of light,[21] since this interaction can be formally obtained from the electromagnetic interaction by the substitution $e\mathcal{A}_\mu \to e\mathcal{A}_\mu + \sqrt{2}\,G_V\, i\bar{\nu}\gamma_\mu\nu$, where $\mathcal{A}_\mu$ is the electromagnetic potential.

In the special case $G_A = 0$, the relation (9) becomes an equality and with equal neutrino and antineutrino cross sections (no VA interference) we obtain

$$\frac{d}{dt}\sigma(\nu T \to \nu X) = \frac{d}{dt}\sigma(\bar{\nu} T \to \bar{\nu} X) = \frac{G_V{}^2}{8\pi^2\alpha^2}t^2\frac{d}{dt}\sigma(eT \to eX)\,. \tag{16}$$

In contrast to Eq. (11), the validity of Eq. (16) does not depend on the assumption of asymptotic chiral symmetry. Also, Eq. (16) should be valid not only for the deep-inelastic region but also for any inclusive or exclusive final states X. Utilizing[19] the available data on the deep-inelastic neutrino and electron scattering, Eq. (16) now implies[22]

$$G_V \simeq G_F\,, \tag{17}$$

or equivalently, if we use Eq. (15), $a \simeq 6 \times 10^{-16}$ cm. If we assume that the elastic leptonic scattering $\bar{\nu}_\mu + e \to \bar{\nu}_\mu + e$ is also due to a one-photon exchange, we find[19] that this value of the neutrino charge radius is consistent with the CERN data[1] for this process. It should, however, be pointed out that the numerical result (17) tends to discredit the interpretation that the neutral-current interactions for the neutrino are electromagnetic in origin. This is because if the neutrino charge radius is a weak effect one expects $a^2 \sim O(G_F)$, so that, from Eq. (15), $G_V \sim O(G_F\alpha)$. However, we should keep in mind that the neutrinos are rather illusive objects, as the problem[23] with solar (electron) neutrinos has recently emphasized, and it may well turn out for reasons not understood at present that the neutrinos possess an anomalously large charge radius.

For the pion production process $\nu N \to \nu N\pi$ it is well known that for low momentum transfers the vector-current contribution is somewhat suppressed compared with the contribution of the axial-vector current. Direct computation of this cross section from Eq. (16) in terms of the available data on the electroproduction of pions will be discussed elsewhere. We might mention here that B. W. Lee's[24] simplified adaptation of Adler's work[25] leads to a result which is consistent with the experimental upper bound on the cross section given by W. Lee,[26] but is somewhat smaller than the more recent ANL results.[5]

It is perhaps too soon to draw any definitive conclusion. The details of these and related calculations (such as $\nu p\to\nu p$) will be presented in a forthcoming publication.

Note added in proof. For Sakurai's theory,[7] the weak neutral current is an SU(3) singlet. In this case, we have in addition to the inequalities (4) the following relation:

$$\sigma(\nu p\to\nu\Lambda K^+)+\sigma(\nu p\to\nu\Sigma^0K^+)=\sigma(\nu p\to\nu p\pi^0)+\sigma(\nu p\to\nu p\eta)$$

in the exact SU(3) limit. One can also derive the $\Delta I=0$ relations

$$\sigma(\nu p\to\nu n\pi^+)=2\sigma(\nu p\to\nu p\pi^0)\,,$$
$$\sigma(\nu p\to\nu\Sigma^+K^0)=2\sigma(\nu p\to\nu\Sigma^0K^+)\,.$$

These relations are also valid if we replace ν by $\bar\nu$. These may be tested in future experiments.

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