Neutrino physics: New flavors? or charm, then color, excitation?

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Investigation of charm, then color, excitation through right-handed, color-octet currents is suggested as a more economical way than adding new flavors for avoiding the conflict of the Weinberg-Salam model with present ν and $\bar{\nu}$ data. The effects from simply adding to the Glashow-Iliopoulos-Maiani current a new right-handed color-octet weak current (the analog of the usual Cabibbo current) are calculated and compared with available charged-current and neutral-current data. A color-octet piece in the weak currents, in general, *does not change* the lowest-order predictions for the Weinberg-Salam model for (i) elastic and quasi-elastic ν- or $\bar{\nu}$-nucleon scattering, (ii) neutral-current-induced parity-violating transitions in atomic physics, and (iii) coherent neutrino-nucleus scattering.

The alternative ideas of "new flavors beyond charm"[1] and of " charm, then color excitation"[2,3] have been generated and developed recently because of measurements of rapid rise in R and of "anomalous" μe events in the 4-GeV region of $e\bar{e}$ annihilation. In neutrino physics, recent analyses[4,5] have shown that models[6] with new flavors can be compatible with present data.[7-10] On the other hand, although it can account for the dimuon production in ν and $\bar{\nu}$ experiments and is in fair agreement with the data on elastic νp and $\bar{\nu}p$ scattering, excitation of charm alone seems not to be adequate to account for the anomalous $d\sigma^{\bar{\nu}}/dy$ distributions or for increases in $\langle y\rangle^{\bar{\nu}}$ and $\sigma^{\bar{\nu}}/\sigma^{\nu}$ observed in high-energy ν and $\bar{\nu}$ charged-current reactions. Therefore, the question that arises is whether excitation of charm, then color, in the economical three-quartet model with integral charges can account for these latter data.

In this paper, to study this possibility phenomenologically, we add a right-handed color-octet[11] weak current to the usual Glashow-Iliopoulos-Maiani, (GIM) current, viz.,

$$J_\mu^{(+)} = \sum_{i=1,2,3} [(\bar{u}^i d_c^i)_L + (\bar{c}^i s_c^i)_L] + \sum_{q=u,d,s} [(\bar{q}^c q^1)_R], \tag{1}$$
$$q^c = q^2\cos\phi + q^3\sin\phi .$$

Here the sum i (q) runs over the three-valued $SU(3)_{\text{color}}$ ($SU(3)_{\text{flavor}}$) index and L (R) denotes the usual left-handed (right-handed) combination of γ matrices. We have chosen the color-octet current to transform in the same way under $SU(3)_{\text{color}}$ as the terms of the left-handed Cabibbo current transform under ordinary $SU(3)_{\text{flavor}}$, and have allowed the color-octet Cabibbo angle ϕ to differ from θ_C. In an $SU(2)\times U(1)$ gauge setting, the neutral current then is given by

$$J_\mu^{(0)} = 2J_\mu^3 - 2\sin^2\theta_W J_\mu^{\text{em}},$$
$$2J_\mu^3 = \sum_{i=1,2,3} [(\bar{u}^i u^i)_L + (\bar{c}^i c^i)_L - (\bar{d}_c^i d_c^i)_L - (\bar{s}_c^i s_c^i)_L] + \sum_{q=u,d,s} [(\bar{q}^c q^c)_R - (\bar{q}^1 q^1)_R], \tag{2}$$

where J_μ^{em} is the usual electromagnetic current in the three-quartet model with integral electric charges, i.e., the charges of the quark quartets are given by the following matrix:

$$Q^{\text{em}} = \begin{array}{c} \\ u \\ d \\ s \\ c \end{array}\begin{array}{c} \text{"one" \ "two" \ "three"} \\ \begin{bmatrix} 0 & 1 & 1 \\ -1 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix} \end{array} . \tag{3}$$

When color is excited in strong interactions, e.g., in the mass spectrum, the difference in the directions "two" and "three" becomes defined and the color-octet Cabibbo angle ϕ then is operationally significant, just as empirical knowledge of the strangeness direction in ordinary $SU(3)_{\text{flavor}}$ makes the usual Cabibbo angle significant.

The color-octet currents in Eqs. (1) and (2) transform as singlets under the ordinary $SU(3)_{\text{flavor}}$. Below color threshold, these right-handed color-octet currents do not contribute, and assuming that the quark parton $u^i(x) = \frac{1}{3}u(x)$, etc., the structure functions and cross sections are identical with those of the single-quartet Weinberg-Salam model. When the threshold is crossed, kinematic effects[12] associated with the production of "heavy quarks" can postpone the effects due to excitation of color; when a heavy quark is produced, the appropriate scaling variable[13] is

$$z_j = \frac{Q^2 + m_j^2}{M[\nu + (\nu^2 + Q^2 + m_j^2)^{1/2}]}, \quad (4)$$

and the structure functions include

$$\theta_j\,(j = 1 \text{ (charm)}, 2 \text{ (color)}, \text{and } 3 \text{ (colored charm)}) = \theta(W - W_j).$$

There are three thresholds— the charm threshold associated with the production of $c\bar{c}$ mesons, the color associated with color-octet $q\bar{q}$ mesons where q denotes u, d, and s quarks, and the colored charm threshold associated with color-octet $c\bar{c}$ mesons (the last is not relevant for the above weak current). For the charm threshold we use $W_1 = 2.25$ GeV since $m_{\Lambda c} \simeq 2.25$ GeV in $\bar{\nu}$ and $m_N + m_D \simeq 2.8$ GeV in ν, and $m_1 = 1.5$ GeV from the J/ψ mass. From the color step in R in $e\bar{e}$ annihilation at about 4 GeV we choose $W_2 = 5.0$ GeV as for the production of color-octet mesons or quark-antiquark pairs at about 4 GeV and treat as a free parameter the effective mass of the struck parton (i.e., current quark) in the color-excited hadronic final state. We find $m_2 = 4.0$ GeV, which is consistent with struck-parton mass-shell production constraints near the color threshold. For production of a color-octet meson or a quark-antiquark pair the constraint $m_2^2 = (k+p)^2 \simeq m_8^2 + 2k \cdot p$, so $m_2^2 \simeq m_8^2$ near threshold where m_8 and k are the invariant mass and momentum of the color-excited state, and $p = q + zP - k$. For formation of a color-excited baryon at[3] about $M_8 \simeq 4.3$ GeV the constraint $M_8^2 \simeq m_2^2 + 2k \cdot (1-z)P$ gives near threshold $m_2^2 \geq M_8(M_8 - 2M)$, or $m_2^2 \gtrsim (3.1\text{ GeV})^2$. (See Figs. 1 and 2.)[14,15]

It is also to be noted that *a color-octet piece in* $J_\mu^{(0)}$ $(J_\mu^{(\pm)})$ *in general does not change* the lowest-order predictions for the Weinberg-Salam model for (i) elastic and quasielastic νp and νn scattering, (ii) parity-violating transitions in atomic physics induced by neutral currents, and (iii) coherent neutrino-nucleus scattering (of relevance to supernova explosions) because only the color-singlet part of $J_\mu^{(0)}$ $(J_\mu^{(\pm)})$ contributes to matrix elements of $J_\mu^{(0)}$ $(J_\mu^{(\pm)})$ between color-singlet states.

We have carried out our calculation of the consequences for inclusive ν and $\bar{\nu}$ scattering of this right-handed color-octet weak current using the

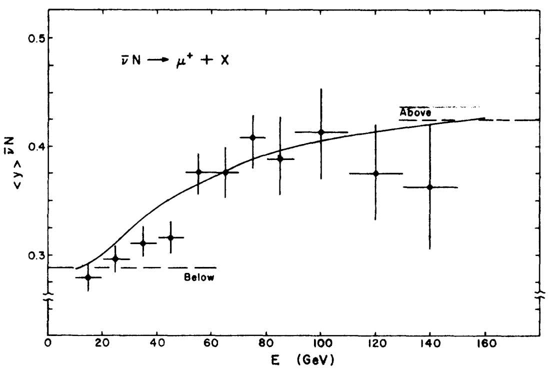

FIG. 1. Average y for scattering of antineutrinos on an isoscalar target in the standard Weinberg-Salam model with a new right-handed color-octet weak current, the analog of the usual Cabibbo current. The flat dashed lines labelled "above" and "below" display the values obtained [directly from Eq. (9)] in the scaling limit for a 5% sea momentum fraction for the regimes "above" both the charm threshold and the color threshold and "below" both of them. The HPWF data points (Ref. 7) are shown.

quark-parton model with spin $\frac{1}{2}$ partons. In listing the predictions, we list first the quantity calculated for the regime "below" all thresholds, i.e., the standard Weinberg-Salam result,[4,5] and then the same quantity but calculated for the regime far "above" all three thresholds. This clearly displays the predicted differences in the two regimes. We also neglect the usual Cabibbo angle since $\cos^2\theta_C \simeq 1$.

We first consider the consequences for charged-current inelastic ν and $\bar{\nu}$ scattering. The differential cross section in the scaling limit is

$$\frac{d^2\sigma^{\nu N, \bar{\nu}N}}{dx\,dy} = \frac{G^2ME}{\pi}\left[(1 - y + \tfrac{1}{2}y^2)F_2^{\nu N, \bar{\nu}N} \mp xy(1 - \tfrac{1}{2}y)F_3^{\nu N, \bar{\nu}N}\right], \quad (5)$$

where N denotes an isoscalar target and the same

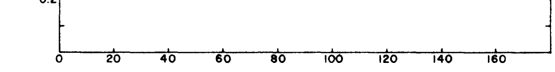

FIG. 2. $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$ curves corresponding to Fig. 1. Solid dots are HPWF data points (Ref. 7) and open squares are CF data (Ref. 8).

equation with N replaced by p holds for a proton target, and $x=Q^2/2M\nu$ and $y=\nu/E$ are the usual scaling variables. We will approximate the sea distributions by assuming $\bar{u}=\bar{d}=s=\bar{s}=\xi$, and $\bar{c}=c=0$ with $\int \xi(z)dz \ll \int u(z)dz$. The isoscalar differential cross sections are found to be

$$\frac{d\sigma^{\nu N}}{dxdy}=\frac{G^2ME}{\pi}\times\begin{cases} x[(u+d)+2\xi(1-y)^2], & \text{below} \\ x\{(u+d)+4\xi \\ \quad +[\tfrac{2}{3}(u+d)+\tfrac{8}{3}\xi](1-y)^2\}, & \text{above} \end{cases} \tag{6}$$

$$\frac{d\sigma^{\bar{\nu} N}}{dxdy}=\frac{G^2ME}{\pi}\times\begin{cases} x[2\xi+(u+d)(1-y)^2], & \text{below} \\ x[\tfrac{2}{3}(u+d)+\tfrac{14}{3}\xi \\ \quad +(u+d+2\xi)(1-y)^2], & \text{above.} \end{cases} \tag{7}$$

This model, then, predicts that $d\sigma^{\nu N}/dy$ should change from ~1 to ~$[1+\frac{2}{3}(1-y)^2]$; the coefficient of $\frac{2}{3}$ is smaller than the 1 of the vector six-quark model and so is less inconsistent with the apparent flat $d\sigma/dy$ behavior of existing data. On the other hand, there is the desirable change of $d\sigma^{\bar{\nu}N}/dy$ from ~$(1-y)^2$ to ~$[\frac{2}{3}+(1-y)^2]$ which could account for the observed behavior of the y anomaly.

The model is successful in predicting that both $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$ and $\langle y\rangle^{\bar{\nu}N}$ increase with energy. It gives

$$\frac{\sigma^{\bar{\nu}N}}{\sigma^{\nu N}}\simeq\begin{cases} \frac{1}{3}\left(1+\frac{8}{3}\frac{\int z(\bar{u}+\bar{d})dz}{\int z(u+d)dz}\right), & \text{below } (0.38) \\ \frac{9}{11}\left(1+\frac{2}{3}\frac{\int z2\xi dz}{\int z(u+d)dz}\right), & \text{above } (0.85) \end{cases} \tag{8}$$

or approximately a 150% increase; and

$$\langle y\rangle^{\bar{\nu}N}\simeq\begin{cases} \frac{1}{4}\left(1+3\frac{\int z(\bar{u}+\bar{d})dz}{\int z(u+d)dz}\right), & \text{below } (0.29) \\ \frac{5}{12}\left(1+\frac{1}{3}\frac{\int z2\xi dz}{\int z(u+d)dz}\right), & \text{above } (0.42) \end{cases} \tag{9}$$

$$\langle y\rangle^{\nu N}\simeq\begin{cases} \frac{1}{2}\left(1-\frac{1}{6}\frac{\int z(\bar{u}+\bar{d})dz}{\int z(u+d)dz}\right), & \text{below } (0.50) \\ \frac{5}{11}, & \text{above } (0.45) \end{cases}$$

so there is only a small change in $\langle y\rangle^{\nu N}$. Shown in the parentheses are the values obtained for the case of a 5% sea momentum fraction.

The predictions of the model for hydrogen experiments, assuming $u(z)=2d(z)$, are

$$\frac{\sigma^{\bar{\nu}p}}{\sigma^{\nu p}}\simeq\begin{cases} \frac{2}{3}\left(1+\frac{7}{6}\frac{\int z\xi dz}{\int zddz}\right), & \text{below } (0.71) \\ \frac{5}{4}\left(1+\frac{1}{6}\frac{\int z\xi dz}{\int zddz}\right), & \text{above } (1.26) \end{cases}$$

$$\langle y\rangle^{\bar{\nu}p}\simeq\begin{cases} \frac{1}{4}\left(1+\frac{3}{2}\frac{\int z\xi dz}{\int zddz}\right), & \text{below } (0.27) \\ \frac{2}{5}\left(1-\frac{1}{16}\frac{\int z\xi dz}{\int zddz}\right), & \text{above } (0.40) \end{cases} \tag{10}$$

and

$$\langle y\rangle^{\nu p}\simeq\begin{cases} \frac{1}{2}\left(1-\frac{1}{4}\frac{\int z\xi dz}{\int zddz}\right), & \text{below } (0.50) \\ \frac{7}{16}\left(1+\frac{1}{14}\frac{\int z\xi dz}{\int zddz}\right), & \text{above } (0.44) \end{cases}$$

so here also $\sigma^{\bar{\nu}p}/\sigma^{\nu p}$ and $\langle y\rangle^{\bar{\nu}p}$ show large increases, whereas $\langle y\rangle^{\nu p}$ does not.

We now turn to the neutral-current processes. Quantities for neutral-current processes are denoted by placing a tilde over the symbol. Neglecting the diagonal terms $\bar{s}s$ and sea components $\bar{u}u$ and $\bar{d}d$, we find the neutral-current inclusive cross section for νp to be, with $x_W=\sin^2\theta_W$,

$$\frac{d\tilde{\sigma}^{\nu p}}{dxdy}=\frac{G^2ME}{\pi}\frac{x}{2}\{(1-\tfrac{4}{3}x_W)^2u+(-1+\tfrac{2}{3}x_W)^2d +[(-\tfrac{4}{3}x_W)^2u+(\tfrac{2}{3}x_W)^2d](1-y)^2\}, \quad \text{below} \tag{11}$$

and, neglecting the diagonal $\bar{c}c$ terms, find

$$\frac{d\tilde{\sigma}^{\nu p}}{dxdy}=\frac{G^2ME}{\pi}\frac{x}{2}\{(1-\tfrac{8}{3}x_W+\tfrac{8}{3}x_W^2)u+(1-\tfrac{4}{3}x_W+\tfrac{4}{3}x_W^2)d +[(\tfrac{2}{3}-\tfrac{4}{3}x_W+\tfrac{8}{3}x_W^2)u +(\tfrac{2}{3}-\tfrac{4}{3}x_W+\tfrac{4}{3}x_W^2)d](1-y)^2\}, \quad \text{above.} \tag{12}$$

The expressions for $d\tilde{\sigma}^{\bar{\nu}p}/dxdy$ are obtained by the interchange $1\leftrightarrow(1-y)^2$, and the νn and $\bar{\nu}n$ cross sections can be obtained from the above results by interchanging the u and d distributions (n denotes a neutron target).

For the convenient value of $x_W\simeq\frac{3}{8}$, the predictions of this model with charm, then color, excitation for the cross-section ratios which involve neutral currents are

	below	above
$R_{\nu N}\equiv\tilde{\sigma}^{\nu N}/\sigma^{\nu N}$	0.23	0.28
$R_{\bar{\nu}N}\equiv\tilde{\sigma}^{\bar{\nu}N}/\sigma^{\bar{\nu}N}$	0.44	0.31
$\tilde{\sigma}^{\bar{\nu}N}/\tilde{\sigma}^{\nu N}$	0.64	0.92.

This model predicts the last quantity to eventually rise. These quantities are to be compared with the corresponding experimental measurements:

	HPWF[7]	CF[8]	CERN
$R_{\nu N}$	0.29 ± 0.04	0.25 ± 0.04	0.28 ± 0.04[10] 0.22 ± 0.03[9]
$R_{\bar{\nu} N}$	0.39 ± 0.10	0.36 ± 0.11	0.38 ± 0.06[10] 0.43 ± 0.12[9]
$\tilde{\sigma}^{\bar{\nu} N}/\tilde{\sigma}^{\nu N}$	$\leq 0.61 \pm 0.25$		0.59 ± 0.14,[10]

where HPWF denotes the Harvard-Pennsylvania-Wisconsin-Fermilab experiment and CF the Caltech-Fermilab experiment. In computing the theoretical ratios we have, of course, assumed that the cross section in the numerator and the cross section in the denominator are both above or both below, in the respective cases.

Finally, as a future test of this model, we give the predictions for hydrogen experiments, which are

	below	above
$R_{\nu p} \equiv \tilde{\sigma}^{\nu p}/\sigma^{\nu p}$	0.31	0.36
$R_{\bar{\nu} p} \equiv \tilde{\sigma}^{\bar{\nu} p}/\sigma^{\bar{\nu} p}$	0.34	0.29
$\tilde{\sigma}^{\bar{\nu} p}/\tilde{\sigma}^{\nu p}$	0.73	1.00 .

It is amusing that for $x_W = \frac{3}{8}$, the asymptotic neutral-current inclusive cross sections for neutrinos and antineutrinos on hydrogen are found to be equal in the present model, unlike the 11/15 ratio of the Weinberg-Salam model and of the asymmetric five-quark model of Achiman, Koller, and Walsh.[6]

We have discussed in this paper possible inclusive effects in ν and $\bar{\nu}$ scattering of charm, then color, excitations. These effects are probably not unique, so we briefly mention here in closing the more striking exclusive experimental signatures[3]:

(i) Mesons or baryons with multiple electric charges (and possibly[2] multiple hypercharges) not present among the usual color-singlet $Q\bar{Q}$ mesons and QQQ baryons. Here Q is a generic label for a quark so $Q = u$, d, s, or c.

(ii) Color-excited states such as color-octet $Q\bar{Q}$ mesons and QQQ baryons, with large widths and possibly large partial widths with missing energy, which do not decay directly by strong couplings into ordinary color-singlet hadrons but only radiatively. The color-octet right-handed currents considered in this paper will give transitions into color-singlet hadrons through cross terms involving the GIM current in second order in the semiweak coupling constant. They do not connect single Q's with color-singlet states.

(iii) Free integrally charged quarks.

In final states which lie in the kinematic regions associated with the antineutrino anomalies, in particular in the high-y and $x \leq 0.15$ region, the presence of a right-handed color-octet weak current implies the occurrence of events which have the signature of the τ particle-antiparticle pairs (signature iii) responsible for the anomalous μe events of $e\bar{e}$ annihilation and the occurrence of events with color-octet $q\bar{q}$ mesons which decay in part into ordinary color-singlet hadrons by radiating high-momentum (a few GeV) photons (signature ii). There will also be events with color-octet baryons. Signatures for color-octet baryons are high-momentum photons from $(qqq)_8 \to (qqq)_1 + \gamma$, and possibly free quarks from $(qqq)_8 \to (qq)_3 + q_{3*}$ if the diquark mass is sufficiently small (the latter is an allowed transition in the case[3] of the popular color-octet vector-meson-exchange mechanism).

Note added in proof. Data from the recent CDHS experiment [M. Holder *et al.*, Phys. Rev. Lett. 39, 433 (1977)] for average y and $\sigma^{\bar{\nu}}/\sigma^{\nu}$ are energy independent from 30 to 200 GeV. Based on a 4-GeV threshold for color excitation as suggested by the data for $e\bar{e}$ annihilation, the present article therefore demonstrates the existence of a significant limit on the presence of right-handed color-octet weak hardronic currents. The requirement that a theory naturally satisfy the normalizations of both the chiral SU(3) × SU(3) algebra and the algebra of the weak gauge group, e.g., SU(2) × U(1) or $SU(2)_L \times SU(2)_R \times U(1)$, strongly constrains the option of left-handed color-octet weak hadronic currents (i.e., *ad hoc* multiplicative factors must occur in lepton currents so as to preserve lepton-hadron universality of the weak interactions).

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[11]Before the recent data containing signatures of charm, many authors studied left-handed color-octet currents to cancel $\Delta Q = 0$, $\Delta S \neq 0$ effects in the three-triplet model in the context of unified gauge theories of weak and electromagnetic interactions. Early papers were by H. J. Lipkin, Phys. Rev. D 7, 1850 (1973) and R. N. Mohapatra, Lett. Nuovo Cimento 6, 53 (1973).

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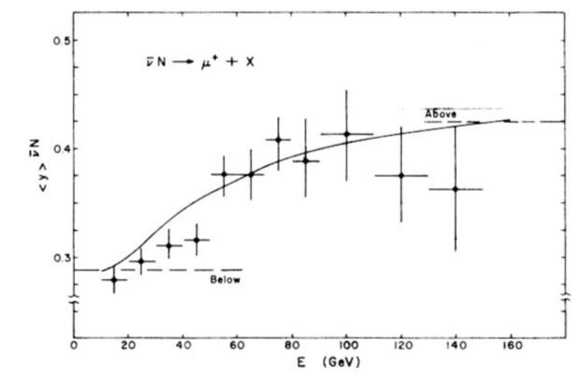

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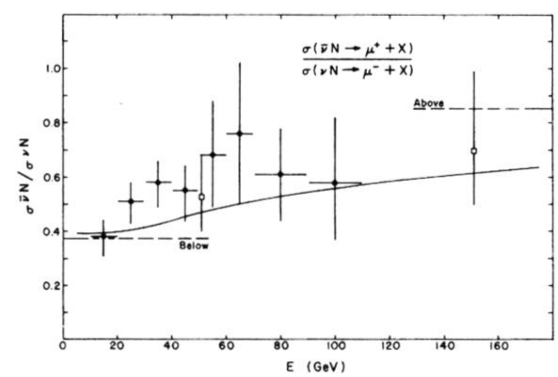

FIG. 2. $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$ curves corresponding to Fig. 1. Solid dots are HPWF data points (Ref. 7) and open squares are CF data (Ref. 8).