CHARMED PARTICLE PRODUCTION BY NEUTRINOS
WITH THE WEINBERG SU(4) CURRENTS

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ABSTRACT

Charmed particle production by neutrinos is investigated with the quark parton model formalism. Emphasis is placed on the largest effects which can be tolerated by the present experimental data as well as those suggested by more conventional parton models.

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Evidence has now been presented which suggests that not only charged but also neutral weak hadron currents occur in nature^{1,2)}. Unlike the charged currents, however, the weak neutral currents appear to be strangeness-conserving³⁾. This observation is puzzling and has led theorists to postulate⁴⁾ the existence of charmed quarks, and hence charmed particles, as a plausible explanation.

Several papers^{5,6)} have explored the consequences of such charmed-current contributions to the Adler and Gross-Llewellyn Smith sum rules, the isospin content and charge-symmetry character of the currents themselves⁷⁾, and the like. In particular we mention the work of De Rújula and Glashow⁷⁾ who worked out the consequences in several gauge theories for various cross-section inequalities based on the structure function positivity constraints. Very recently^{*}, Altarelli, Cabibbo, Maiani and Petronzio⁸⁾ have explored the consequences in a quark parton model using particular parton distribution functions deduced from inelastic electroproduction.

We wish to explore here with the Weinberg model⁹⁾ the scaling-region behaviour due to the opening of new charmed particle production channels. While we use the quark parton formalism, unlike Ref. 8 we do not restrict our attention to a particular parton model but rather use directly the bounds imposed by the present data on neutrino- and electroproduction. Thus we can deduce the maximum possible effect on the scaling behaviour which can arise from charmed hadron production. We confine our attention to the simple Weinberg model⁹⁾ since so far it is capable of explaining¹⁰⁻¹²⁾ the present neutrino data^{1,2)}.

In the Weinberg model of symmetry-breaking based on the gauge group $SU(2) \times U(1)$, two left-handed doublets and four right-handed singlets are introduced involving the quarks p , n , and λ together with the charmed quark p' . The charged and neutral weak currents of fractionally charged Gell-Mann-Zweig quarks are given by

$$j_{\mu}^{(+)} = \bar{p} \gamma_{\mu} (1 + \gamma_5) (n \cos \theta_c + \lambda \sin \theta_c) + \bar{p}' \gamma_{\mu} (1 + \gamma_5) (-n \sin \theta_c + \lambda \cos \theta_c) \quad (1a)$$

$$j_{\mu}^{(-)} = j_{\mu}^{(+)*} \quad (1b)$$

*) Reference 8 came to the author's attention while this manuscript was in preparation.

$$j_\mu^{(0)} = \frac{1}{2} \bar{p}' \gamma_\mu (1 + \gamma_5) p' + \frac{1}{2} \bar{p} \gamma_\mu (1 + \gamma_5) p - \frac{1}{2} \bar{n} \gamma_\mu (1 + \gamma_5) n - \frac{1}{2} \bar{\lambda} \gamma_\mu (1 + \gamma_5) \lambda - 2 \sin^2 \theta_w j_\mu^{(em)} \quad (1c)$$

while the electromagnetic current is just

$$j_\mu^{(em)} = \frac{2}{3} (\bar{p}' \gamma_\mu p' + \bar{p} \gamma_\mu p) - \frac{1}{3} (\bar{n} \gamma_\mu n + \bar{\lambda} \gamma_\mu \lambda) \quad (2)$$

in terms of the Cabibbo angle θ_c and the Weinberg angle θ_w . These quark currents result in the following weak hadronic currents

$$J_\mu^{(\pm)} = \cos \theta_c (V-A)_\mu^{1 \pm i 2} + \sin \theta_c (V-A)_\mu^{4 \pm i 5} - \sin \theta_c (V-A)_\mu^{12 \pm i 13} + \cos \theta_c (V-A)_\mu^{14 \pm i 15} \quad (3a)$$

$$J_\mu^{(0)} = (V-A)_\mu^{3 + \frac{1}{\sqrt{3}} 8} - \frac{1}{2} \sqrt{\frac{2}{3}} (V-A)_\mu^0 + \frac{1}{\sqrt{2}} (V-A)_\mu^{16} - 2 \sin^2 \theta_w J_\mu^{(em)} \quad (3b)$$

expressed in terms of the electromagnetic current

$$J_\mu^{(em)} = V_\mu^{3 + \frac{1}{\sqrt{3}} 8} + \frac{2\sqrt{2}}{3} V_\mu^{16} \quad (4)$$

Here we use SU(4) notation where the superscript j refers to the 4×4 matrix λ_j : j = 1 through 8 identifies the SU(3) submatrices, j = 0 the U(3) singlet, j = 10 through 15 the charm-changing matrices and j = 16 the charm-conserving matrix which connects p' to itself.

It is clear from Eqs. (3) and (4) that the (charm-conserving) weak neutral and electromagnetic currents can only account for associated charmed-particle production whereas the (charm-changing) charged current can result in single production of a charmed hadron with ordinary uncharmed targets found in nature. Moreover, the associated production of charmed particles by $J_\mu^{(0)}$ and $J_\mu^{(em)}$ will not result in a new Bjorken scaling region above threshold while single charmed particle production by $J_\mu^{(\pm)}$ results in the transition to a new scaling behaviour as the third and fourth terms in Eq. (3a) come into play. Unlike strange

particle production which is suppressed by $\sin^2 \theta_c \approx 0.06$, charmed particle production is not so suppressed. Hence the effect can in principle be large.

Whether or not the transition from one scaling region to another results in a sizeable effect as energies go beyond the charmed particle threshold depends critically on the strange-quark content of the target nucleon. We address ourselves to this matter by going to the quark-parton model framework in order to deduce the allowed range of parameters permitted by the present experimental information.

In Feynman's notation¹³⁾ the neutrino and antineutrino charged-current cross-sections on nucleons below charmed-particle threshold are given by

$$\sigma_{ch}^{\nu N} = \sigma_0 \left[\frac{1}{3} \alpha_A + \cos^2 \theta_c + \alpha_S \sin^2 \theta_c \right] (U+D) \quad (5a)$$

$$\sigma_{ch}^{\bar{\nu} N} = \sigma_0 \left[\frac{1}{3} + \alpha_A \cos^2 \theta_c + \alpha_S \sin^2 \theta_c \right] (U+D) \quad (5b)$$

in terms of $\sigma_0 = G^2 M E / \pi$,

$$\alpha_A = (\bar{U} + \bar{D}) / (U+D)$$

$$\alpha_S = (S + \bar{S}) / (U+D)$$

where U, D, S, $\bar{U}$, $\bar{D}$, and $\bar{S}$ are the fractional longitudinal momenta carried by the p, n, λ , $\bar{p}$, $\bar{n}$, and $\bar{\lambda}$ quarks and antiquarks in the proton. The electromagnetic integral, on the other hand, has the form

$$\begin{aligned} I^{ep} + I^{en} &= 2 \int_0^1 dx F_2^{eN}(x) \\ &= \left[\frac{5}{9} (1 + \alpha_A) + \frac{4}{9} \alpha_c + \frac{1}{9} \alpha_S \right] (U+D) \end{aligned} \quad (6)$$

with

$$\alpha_c = (C + \bar{C}) / (U+D)$$

where C and $\bar{C}$ are the fractional momenta carried by the charmed quarks p' and $\bar{p}'$.

The following experimental results^{*)} have been obtained at CERN¹⁴⁾ and SLAC¹⁵⁾:

$$\sigma_{ch}^{\nu N} = \sigma_0 (0.47 \pm 0.02) \quad (7a)$$

$$\sigma_{ch}^{\bar{\nu} N} = \sigma_0 (0.17 \pm 0.01) \quad (7b)$$

$$I^{\nu p} + I^{\nu n} = 0.29 \pm 0.02 \quad (7c)$$

If we make the reasonable assumption that the α 's are small so that most of the momentum of the proton is carried by the p and n valence quarks, we can derive the following relations from Eqs. (5), (6) and (7):

$$u + D = 0.49 \pm 0.04 \quad (8a)$$

$$\bar{u} + \bar{D} \leq 0.01 \begin{matrix} +0.02 \\ -0.01 \end{matrix} \quad (8b)$$

$$s + \bar{s} \leq 0.08 \begin{matrix} +0.18 \\ -0.08 \end{matrix} \quad (8c)$$

$$c + \bar{c} \leq 0.02 \begin{matrix} +0.05 \\ -0.02 \end{matrix} \quad (8d)$$

where the indicated spreads reflect one standard deviation uncertainty. While the bounds on the $\bar{p}$, $\bar{n}$, p' , and $\bar{p}'$ quark momentum contributions are low, the bounds on the strange λ and $\bar{\lambda}$ contributions are not so tight.

Turning our attention to the new scaling region that may be reached above the charmed-hadron production threshold, we find the following charged-current cross-sections in the parton model:

$$\sigma_{ch}^{\nu N} = \sigma_0 \left[1 + \alpha_s + \frac{1}{3}(\alpha_A + \alpha_c) \right] (u + D) \quad (9a)$$

*) The number quoted in Eq. (7c) is a reasonable interpretation of the results reported in Ref. 15.

$$\sigma_{ch}^{\bar{u}N} = \sigma_0 \left[\frac{1}{3}(1+\alpha_c) + \alpha_A + \alpha_S \right] (U+D) \quad (9b)$$

The normalized y-distributions are also of interest and in the new scaling region have the form

$$\left(\frac{1}{\sigma} \frac{d\sigma}{dy} \right)_{ch}^{\bar{u}N} = \left[1 + \alpha_S + (\alpha_A + \alpha_c)(1-y)^2 \right] \left[1 + \alpha_S + \frac{1}{3}(\alpha_A + \alpha_c) \right]^{-1} \quad (10a)$$

$$\left(\frac{1}{\sigma} \frac{d\sigma}{dy} \right)_{ch}^{\bar{u}N} = \left[(1+\alpha_c)(1-y)^2 + \alpha_A + \alpha_S \right] \left[\frac{1}{3}(1+\alpha_c) + \alpha_A + \alpha_S \right]^{-1} \quad (10b)$$

in contrast with their behaviour in the scaling region below the charmed particle threshold:

$$\left(\frac{1}{\sigma} \frac{d\sigma}{dy} \right)_{ch}^{\bar{u}N} = \left[\cos^2 \theta_c + \alpha_S \sin^2 \theta_c + \alpha_A (1-y)^2 \right] \left[\cos^2 \theta_c + \alpha_S \sin^2 \theta_c + \frac{1}{3} \alpha_A \right]^{-1} \quad (11a)$$

$$\left(\frac{1}{\sigma} \frac{d\sigma}{dy} \right)_{ch}^{\bar{u}N} = \left[(1-y)^2 + \alpha_A \cos^2 \theta_c + \alpha_S \sin^2 \theta_c \right] \left[\frac{1}{3} + \alpha_A \cos^2 \theta_c + \alpha_S \sin^2 \theta_c \right]^{-1} \quad (11b)$$

Note that in the scaling region above the charmed particle threshold, the Cabibbo angle no longer enters the cross-sections and y-distributions with the result that the strange and charmed quark contributions are no longer suppressed.

To illustrate the size of the effects that may be anticipated in the higher energy scaling region, we adopt two different sets of values for the parton parameters admissible according to the inequalities given in (8). The first set I

$$\begin{aligned} U+D &= 0.49, & \bar{U}+\bar{D} &= 0.01 \\ S+\bar{S} &= 0.10, & C+\bar{C} &= 0.01 \end{aligned} \quad (I)$$

emphasizes the strange quark contribution and gives us an idea of just how large the charmed particle production effect can be^{*)}. The second set illustrates a more conventional isoscalar quark sea background effect¹⁶⁾ and is taken to be

$$u + D = 0.49, \quad \bar{u} + \bar{D} = s + \bar{s} = c + \bar{c} = 0.02 \quad (\text{II})$$

The results for the energy dependence of the cross-sections and normalized y -distributions are shown in Figs. 1 and 2 for the two cases of interest. The energy scale in Fig. 1 is merely illustrative as the simple quark parton model says nothing about the charm production threshold. We have shown a transition region to "guide the eye" in proceeding from one scaling region to the other. In principle, the threshold for charmed particle production in the neutrino reaction where $\Delta C = +1$ could be higher or lower than that in the antineutrino reaction where $\Delta C = -1$.

To conclude, we emphasize that the new scaling region due to charmed-hadron production will only show up in charged-current neutrino and antineutrino reactions and will not appear in the neutral-current weak and electromagnetic inclusive reactions. The size of the effect depends critically on the strange-quark contribution as evidenced by the results for the two cases I and II considered.

If it should turn out that a breakdown of scaling appears in the experimental data but that the effect is considerably larger than that shown in Figs. 1 and 2, it is unlikely that the phenomenon responsible for the effect is due to charmed-particle production: case I admits values for $s + \bar{s}$ which are just tolerated by the present experimental data. While we have demonstrated this only for the Weinberg model, other gauge theories which suppress the $n \rightarrow p'$ quark transition will yield similar results.

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*) Although values larger than 0.10 are allowed by (8c) for $s + \bar{s}$, one finds that such values in fact lead to predictions which are inconsistent with the neutral-current results quoted in Refs. 1 and 2.

Figure captions

Fig. 1 : Energy dependence of the charged-current inclusive neutrino cross-sections. The extrapolated straight lines obtain with no charmed-particle production, while the broken and dotted curves refer to charmed particle production for cases I and II respectively. The indicated threshold at 80 GeV and transition behaviours from one scaling region to the other have no special significance and are purely illustrative.

Fig. 2 : Normalized y -distributions for charged-current inclusive neutrino reactions in the scaling regions below (solid curves) and above charmed-particle production thresholds in cases I (broken curves) and II (dotted curves).

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Fig. 1

Fig. 2