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[1]See M. Barnett and F. Martin, SLAC Report No. SLAC-PUB-1892, 1977 (unpublished); I. Karlziner and J. D. Sullivan, University of Illinois Report No. ILL-TH-77-18, 1977 (unpublished).

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[7]A smaller penetration requirement risks contamination by neutral-current interactions. See F. S. Merritt *et al.*, California Institute of Technology Report No. CALT 68-600, 1977 (to be published).

[8]$E_h^{\max} = E/(1+\kappa_1)$ with $\kappa_1 = 2M/E\theta_1^2$, M the nucleon (target) mass, and θ_1 the maximum muon angle subtended.

[9]The spectra of events versus E_h can also be compared with mean neutrino energy, E, to determine $\langle y\rangle$. This will be the subject of a subsequent communication [B. C. Barish *et al.*, California Institute of Technology Report No. CALT 68-606 (to be published).

[10]This difference could result from a 10-GeV boson propagator, but that hypothesis gives a bad fit to our data. Our data alone gives $M_w > 30$ GeV (90% confidence level) with no scale breaking. If a scale-breaking Q^2 dependence that lowers our sensitivity (e.g., $\langle Q^2/E\rangle \propto E^{-0.15}$) is allowed, our mass limit is $M_w > 20$ GeV.

[11]A. Benvenuti *et al.*, Phys. Rev. Lett. 37, 189 (1976).

[12]The quoted errors include all of our known uncertainties. An energy-dependent rise in the slope σ/E might result from mismeasurement of the $\pi/K/p$ ratios and/or misidentification of $\bar{\nu}_\pi$- or $\bar{\nu}_K$-induced events due to mismeasurement of the secondary muon. However, our measured $(1/E)d\sigma/dy$ at $y=0$ (see Ref. 6), which also depends on these effects, show no energy dependence.

[13]M. Holder *et al.*, Phys. Rev. Lett. 39, 433 (1977).

Quantum Chromodynamics Predictions for the Associated Production of Charm by Neutrinos

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Cross sections for the inclusive production of charm-anticharm pairs in the hadron showers of neutrino scattering are calculated within framework of quantum chromodynamics. A branching ratio of less than 10^{-3}, insufficient to account for the like-sign dimuons observed by Barish *et al.*, Benvenuti *et al.*, and Holder *et al.* and trimuons observed by Barish *et al.* and Benvenuti *et al.*, is obtained for $\alpha_s = 0.4$ at values of x between 0.05 and 0.3, and $\nu \sim 50$–75 GeV.

Trimuons[1,2] and like-sign dimuons[3-5] have recently been observed in high-energy neutrino experiments. It has been proposed[6] that the production and subsequent decay of new heavy leptons ($m \sim 10$ GeV) are responsible for these events. However, at least in the case of the like-sign dimuons, the events may be accounted for through the associated production of charm-anticharm pairs in (0.5–1)% of the hadron showers.[4,7] Hence the heavy-lepton interpretation of the multimuon events must be measured against at least this alternative.

In a recent Letter, Bletzacker, Nieh, and Soni[8] have presented a phenomenological model of $c\bar{c}$ pair production in the diffractive (small-x) region in order to account for the kinematic distributions of the multimuons. Since the publication of this work, however, a "large" sample of 47 $\mu^-\mu^-$ events has been reported[5] in a ν-Fe experiment by Holder *et al.* The background from π^- and K^- decay is estimated to contribute 30 ± 7 events, so that it is possible that there are 17 ± 7 $\mu^-\mu^-$ events of direct origin. The $\langle x_{\rm vis}\rangle$ of all the events is 0.28, so that if there are events of direct origin, it is likely that they are *not* in the diffractive region. (The seven events reported in Ref. 3 also have $\langle x_{\rm vis}\rangle \simeq 0.2$.) In addition, the work of Ref. 8 does not provide a theoretical basis for the overall normalization of the cross section for the associated production of charmed hadrons.

Thus, it is of considerable practical interest to provide a theoretical model for inclusive charm-anticharm production in the nondiffractive ("normal x") region of ν-nucleus scattering. Such a model, based on the standard SU(3) color gauge theory of the strong interactions (quantum chromodynamics, "QCD") is presented in this paper.

It will be seen that the estimates obtained, for average values[9] of the QCD coupling constant $\alpha_s(\mu) \simeq 0.4$ and the charmed-quark mass $m_c(\mu) \simeq 1.6$ GeV (for 3 GeV $\leq \mu \leq$ 13 GeV), are very strong functions of ν, the total hadron energy, and weak functions of x. In the range of the experiments of Holder *et al.*[5] ($\langle x\rangle \sim 0.3$, $\langle \nu\rangle \sim 70$ GeV), the branching ratio is predicted to be about 6×10^{-3}, a factor of 10 too small to account for the data.

The model is essentially described by the graphs in Fig. 1(a). A parton in a nucleon is struck by a W, and emits (or preemits) a timelike color gluon, which subsequently "decays" into a $c\bar{c}$ pair. {Other contributions, such as the emission of the $c\bar{c}$ pair by one of the spectator partons [depicted in Fig. 1(b)], are expected to be small because they involve large momentum transfers along more than one gluon line, resulting in extra factors of α_s^2.} All dressings of the quarks in the final state are assumed (as usual) to proceed with unit probability, and all momenta are integrated over. The arithmetic is straightforward but tedious, and consists primarily of squaring the amplitude, integrating over phase space, and subsequently identifying the contributions of a single parton to the structure functions W_1, W_2, and W_3. These are then convoluted with parton distribution functions[10] to obtain the contribution of inclusive associated charm production to neutrino-nucleon scattering,

$$d\sigma_{\nu\bar{\nu}}{}^{c\bar{c}}/dx\,dy = (G^2ME_\nu/\pi)[\tfrac{1}{2}y^2xF_1{}^{c\bar{c}} + (1-y)F_2{}^{c\bar{c}} \mp y(1-\tfrac{1}{2}y)xF_3{}^{c\bar{c}}], \tag{1}$$

where $F_1{}^{c\bar{c}} \equiv 2M_NW_1{}^{c\bar{c}}$, $F_2 \equiv \nu W_2{}^{c\bar{c}}$, $F_3 \equiv \nu W_3{}^{c\bar{c}}$, and $y=\nu/E_\nu$, with W_1, W_2, and W_3 defined in the standard manner.[11] The nucleon structure functions W_i are given in terms of parton structure functions w_i by

$$W_{1,2} = \int (d\eta/\eta)w_{1,2}(q^2,\nu,\eta)[q(\eta)+\bar{q}(\eta)],$$
$$W_3 = \int (d\eta/\eta)w_3(q^2,\nu,\eta)[q(\eta)-\bar{q}(\eta)], \tag{2}$$

where $q(\eta)=\frac{1}{2}[u(\eta)+d(\eta)]$ and $\bar{q}(\eta)=\frac{1}{2}[\bar{u}(\eta)+\bar{d}(\eta)]$, and u, d ($\bar{u}$, $\bar{d}$) are the up and down quark (antiquark) densities in the proton, as a function of the longitudinal momentum fraction η. (Note that $\eta \neq x$.)

In order to simplify the arithmetic to some extent, all the light-quark masses have been set equal to zero. In that case, most of the phase-space calculation can be performed analytically. There remains a twofold numerical integration: over τ, the square of the c.m. energy of the $c\bar{c}$ pair, and over η. For fixed $x=-q^2/2M_N\nu$, ν, and η, the range of τ is

$$4m_c{}^2 \leq \tau \leq 2M_N\nu(\eta - x),$$

whereas η ranges over the values $\eta_{\min}=x+4m_c{}^2/2M_N\nu$ to 1. From this we note the important fact *that for moderate* ν *(*$\nu<100$ *GeV),* $\eta_{\min}>0.05$ *even for* x *close to zero. Hence wee partons play no role in the calculation, and the model is expected to give meaningful results even for very small* x *(*$x<0.1$*).*

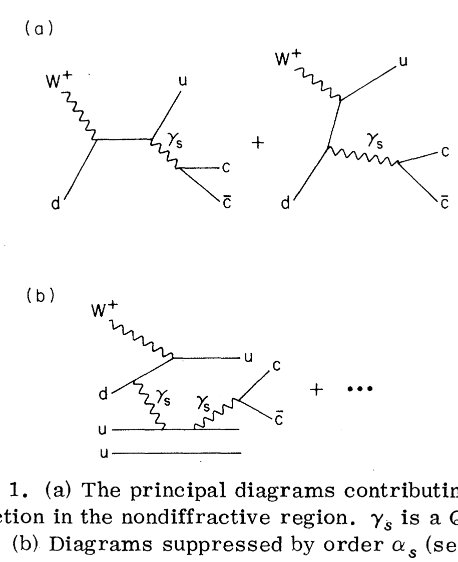

FIG. 1. (a) The principal diagrams contributing to $c\bar{c}$ production in the nondiffractive region. γ_s is a QCD gluon. (b) Diagrams suppressed by order α_s (see text).

From Eq. (1), the theoretical branching ratio to charm-anticharm pairs in neutrino scattering is

$$B_{\nu N}{}^{c\bar{c}} = \frac{\frac{1}{2}y^2xF_1{}^{c\bar{c}} + (1-y)F_2{}^{c\bar{c}} - y(1-\frac{1}{2}y)xF_3{}^{c\bar{c}}}{x(u+d)+(1-y)^2x(\bar{u}+\bar{d})}, \tag{3}$$

where, for consistency, we have made use of the parton-model relations[11] $xF_1{}^{\nu N}=F_2{}^{\nu N}=x(u+d+\bar{u}+\bar{d})$, $-xF_3=x(u+d-\bar{u}-\bar{d})$.

In Fig. 2 are plotted some sample results for $y=0.5$. The branching ratio is slowly varying in x, but very rapidly varying in ν, so that a comparison with experiment would require a fairly accurate knowledge of $\langle\nu\rangle$ for the events in question. For the 17 ± 7 possible events of Ref. 4, we may estimate that $\langle x\rangle \sim 0.3$, $\langle\nu\rangle \simeq 70$ GeV (the lat-

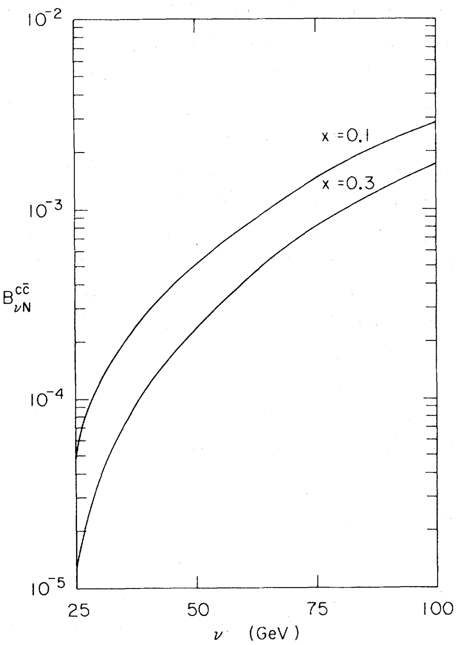

FIG. 2. Branching ratio $B_{\nu N}{}^{c\bar{c}} \equiv [d\sigma(\nu N \to \mu^- c\bar{c}X)/dxdy][d\sigma(\nu N \to \mu^- X)dxdy]^{-1}$, evaluated at $y = 0.5$, vs total hadron energy ν.

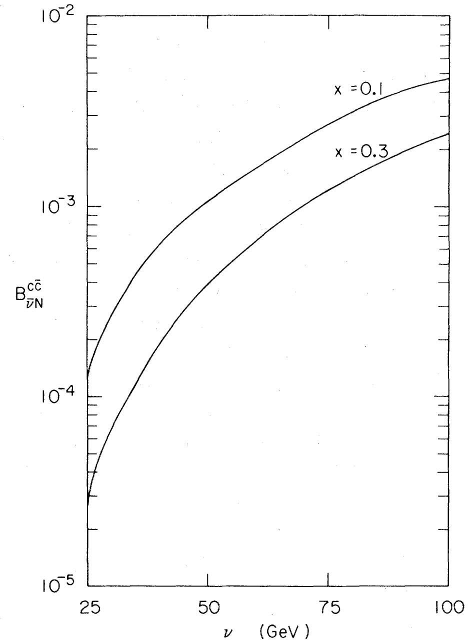

FIG. 3. Branching ratio $B_{\bar{\nu} N}{}^{c\bar{c}} \equiv [d\sigma(\bar{\nu} N \to \mu^+ c\bar{c}X)/dxdy][d\sigma(\bar{\nu} N \to \mu^+ X)/dxdy]^{-1}$, evaluated at $y = 0.5$, vs total hadron energy ν.

ter being obtained from the stated values of $\langle y \rangle$, $\langle E_{\mu_1} \rangle$, and $\langle E_{\mu_2} \rangle$), and hence (from Fig. 2) propose a theoretical branching ratio of about 0.6×10^{-3} for associated production of charmed-anticharmed pairs in hadron showers of neutrino collisions. Folded with a branching of 0.15 of $c \to \mu^+ \ldots$, and a detection efficiency[5] of 0.3, we are led to a branching ratio of 2.7×10^{-5} for $\mu^-\mu^-$ pairs. This is a factor of 10 too small to account for the experimental results. The corresponding trimuon branching from $c\bar{c}$ pairs is then predicted to be 3×10^{-6}, also a factor of 10 smaller than experiment.[1,2]

For completeness I have plotted in Fig. 3 the branching into charm-anticharm pairs for $\bar{\nu}N$ experiments. The relevant formula [corresponding to Eq. (3)] is

$$B_{\bar{\nu} N}{}^{c\bar{c}} = \frac{\frac{1}{2} y^2 x F_1{}^{c\bar{c}} + (1-y) F_2{}^{c\bar{c}} + y(1 - \frac{1}{2} y) x F_3{}^{c\bar{c}}}{x(u+d)(1-y)^2 + x(\bar{u}+\bar{d})} . \tag{4}$$

Except for being slightly larger, the behavior of this branching ratio is similar to that in the case of νN. The branching into multimuons can be found as before.

Curves for smaller values of x ($x = 0.01$ and 0.05) have also been calculated, but not plotted. They differ by less than 30% from the $x = 0.1$ curves in Figs. 2 and 3.

To conclude, I have calculated within the framework of QCD the cross section for the inclusive production of charm-anticharm pairs in neutrino-nucleus scattering. I have found values of the order of 10^{-3} at presently available energies. This is insufficient to account for the like-sign dimuon events observed by Barish *et al.*, Benvenuti *et al.*, and Holder *et al.*, and trimuons observed by Barish *et al.*, and Benvenuti *et al.* *If these events persist* at the rates quoted, we would tend, in the light of this calculation, to consider more seriously the heavy-lepton alternative, or a recalculation of $\pi/K \to \mu$ background.

There remains the question: Is the mechanism proposed in this paper the dominant one for associated charm production in neutrino interactions? One would expect this to be so in the scaling region, $Q^2 \gtrsim 1$ GeV^2. For $\langle \nu \rangle \sim 50$ GeV, this means $x \gtrsim 0.01$. Hence one would not expect a virtual hadronic diffractive mechanism to play a significant role in the like-sign dimuon production at $x \sim 0.2$–0.3 discussed in this paper.[12]

Calculational details are deferred to a later publication.

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[12]The case of μN scattering is considerably different: The presence of a substantial ψ component in the virtual photon [F. E. Close, D. Scott, and D. Sivers, Nucl. Phys. B117, 134 (1976)] introduces a possibly dominant $c\bar{c}$ production mechansim into electroproduction which is not present in νN and $\bar{\nu} N$ interactions [see also D. P. Roy, Phys. Lett. 63B, 76 (1977)]. There are also additional parton diagrams in this case, due to the presence of gluons in the proton. These given contributions of order α_s.

Study of Pion-Absorption Mechanisms in ^{4}He and Other Nuclei

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The spectrum and yield of protons produced by 60-, 100-, and 200-MeV π^+ and π^- beams on targets of ^{4}He, ^{12}C, ^{62}Ni, and ^{181}Ta have been measured at 45° and 90°. A distinct high-energy component is seen in the protons from ^{4}He, which is consistent with a two-body absorption mechanism. Its cross section at 220 MeV is somewhat larger than calculated from the π^+ + D process. Possible evidence is also seen for multinucleon absorption modes. The data on heavier nuclei are consistent with earlier experiments.

Our knowledge and understanding of mechanisms whereby pions interact and are absorbed in nuclei is still very nebulous. In order to study such processes the present measurements included the simplest of "complex nuclei," ^{4}He, as one of the targets. The pion beam of the LEP channel at LAMPF (Clinton P. Anderson Meson Physics Facility) were used to study proton spectra under the conditions described in the abstract.

The experimental techniques were similar to those described in a recent paper.[1] A liquid He target was used; it was constructed such a way that the cryostat contributed $\lesssim 6\%$ of the protons seen by the counter telescopes. Protons were