Mechanism for associated production of charm and multimuon events in neutrino-nucleon scattering

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A mechanism is proposed for the associated production of D, D^- mesons in $\nu_\mu N$, $\nu^-_\mu N$ interactions, making possible a unique explanation of events involving the formation of trimuons of nonelectromagnetic nature and singly charged dimuons.

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The observation of multimuon events in neutrino-nucleon scattering[1–5] has aroused interest in attempting to explain them as the result of the formation and decay of new heavy leptons or new quarks.[6–9] It follows from the results of Ref. 2, however, that less than 17% of the trimuons can be explained by the heavy lepton (M^-, M°) decay mechanism, while the decay of heavy quarks (b, t) contributes less than 10% to the 3μ event. An electromagnetic mechanism, consisting of the fact that quarks or a muon emit a bremsstrahlung $\mu^-\mu^+$ pair, has been proposed[10–13] to explain multimuon events. According to the estimates of various authors,[10–12] this mechanism gives $R^{\nu}_{3\mu} \equiv \sigma(\nu_\mu N \to \mu^-\mu^-\mu^+ + ...)/\sigma(\nu\mu N \to \mu X^-) \approx (1\text{–}2)\times 10^{-5}$ for the ratio of the number of 3μ events to the number of one-muon events; this agrees with the experimental estimate[2] of the electromagnetic contribution $R^{\nu}_{3\mu} = (0.8 \pm 0.4)\times 10^{-5}$. At the same time the electromagnetic mechanism cannot explain events involving the formation of singly charged dimuons because it predicts $R^{\nu}_{\mu\mu} \equiv \sigma(\nu_\mu N \to \mu^-\mu^- + ...)/\sigma(_\mu N \to \mu^- X) < R^{\nu}_{3\mu}$, which is clearly contradictory to the experimental ratio $< R^{\nu}_{\nu\mu} / < R^{\nu}_{3\mu} \sim 10$.[1,2,4]

In order to understand the mechanism for the formation of singly charged dimuons and trimuons it is necessary to consider those relationships which follow from available experimental data.[1,5] If the fast muon in the reaction $\nu^\mu_N \to \mu^-\mu^-\mu^+ + ...$ is denoted by μ_1^- and the slow by μ_2^-, μ_3^+ (correspondingly, in $\mu^-\mu^-$ events this will be μ_1^-, μ_2^-), then the average energy is $\langle E_{\mu_1} \rangle \gg \langle E_{\mu_2^-} \rangle$ (or $\langle E_{\mu_3^+} \rangle$ for 3μ events, in which $\langle E_{\mu_2} \rangle \sim \langle E_{\mu_3} \rangle$). The invariant masses of the systems $\mu_1^-\mu_2^-\mu_3^+$, $\mu_1^-\mu_2^-$, $\mu_1^-\mu_3^+$ are of the same order of magnitude and much greater than the invariant mass of the

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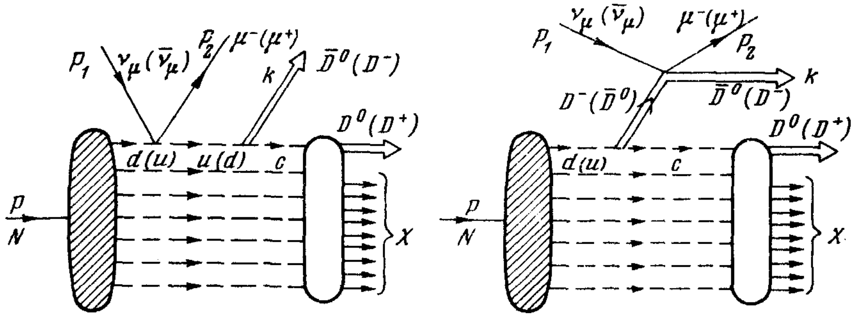

FIG. 1. Diagrams of processes (1) and (2) in quark-parton model.

system $\mu_2^-\mu_3^+$. The distributions with respect to the azimuth angle between the momentums of μ_1^- and μ_2^-, μ_1^- and μ_3^+, μ_1^- and μ_2^-, μ_3^+ in the plane, perpendicular to the momentum of the initial neutrino, have a maximum at a value of 180° both in the case of $\mu^-\mu^-$ as well as the case of 3μ events. These relationships make it possible to conclude that in the events being considered the μ_1^- is formed at a lepton, while the μ_2^- (and the μ_3^+ in trimuons) is formed at hadron peaks, with the μ_2^-, μ_3^+ being strongly considered. The electromagnetic mechanism describes well the above-indicated features of the 3μ events. It follows from Ref. 2, however, that the fraction of trimuons $R^{\nu}_{\mu\mu}/R^{\nu}_{3\mu} \sim 10$ as well as the analogies in the energy and azimuth angle distributions of the $\mu_1^-\mu_2^-$ in the $\mu^-\mu^-$ events suggest that these fractions of trimuons and singly charged dimuons are fromed as the result of the action of the same mechanism, related to the production of charmed particles. Either trimuons or singly charged dimuons appear, depending along which channel (lepton or hadron) the charmed decays.

This paper examines the mechanism for associated production of D, $\bar{D}$ mesons in the processes:

$$\nu_\mu + N \to \mu^- + \bar{D}^\circ + D^\circ + X, \tag{1}$$

$$\bar{\nu}_\mu + N \to \mu^+ + D^- + D^{\mp} + X, \tag{2}$$

where X denotes an arbitrary hadron state. Diagrams of the processes (1) and (2) are shown in Fig. 1, with it being assumed that the transition of the virtual light quark into real c quark and $\bar{D}$ mesons is not accompanied by the emission of other hadrons, and subsequently the c quark undergoes a definite transition into a D meson. Using the notations in Fig. 1 and introducing the variables $x = -(q^2/2qp)$, $y = 1 - (E'/E)$, $\eta = -(\tilde{q}^2/2\tilde{q}p)$, $z = (E_{\bar{D}}/E_q)$, where $q = p_1 - p_2$, $\tilde{q} = q - k$, E and E' are the energies of the $\nu_\mu(\bar{\nu}_\mu)$ and $\mu^-(\mu^+)$ in the laboratory system, $E_{\bar{D}}$ and E_q are the energies of the $\bar{D}$ meson and the light quark in the Breit system, we obtain the differential cross sections of processes (1) and (2), integrated over the momentums of all hadrons, except the $\bar{D}$ meson, in the following form:

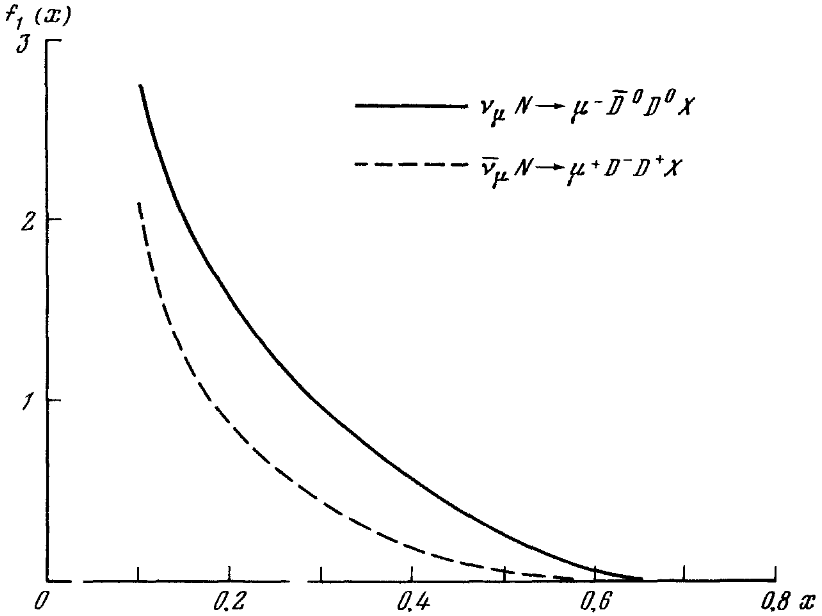

FIG. 2. Dependence of the quantity $f_1(x) = (d\sigma/dx)/[(G^2ME/\pi)\,\gamma/64\pi^2]$ on the variable x for processes (1) and (2).

$$\frac{d\sigma}{dx\,dy\,d\eta\,dz} = \left(\frac{G^2ME}{\pi}\right)\frac{\gamma x[u(x)+d(x)]}{32\pi^2\eta^2(\eta-2)^2\,\mathrm{sign}(\eta-2)}\left\{\frac{2\eta^2F(y)}{\eta-1}(\eta-2-z) + \frac{\eta(\eta-2)^2(1-y)}{(\eta z-2\epsilon)} + z\eta^2(1-y) - (\eta-2-z)[\pm y(2-y)\eta + y^2 + 6(1-y)]\right\}. \qquad (3)$$

Here $u(x)$, $d(x)$ are the Feynman quark-parton distributions, the $(\pm)$ signs refer to processes (1) and (2), respectively, the function $F(y)$ has the form

$$F(y) = \begin{cases} 1, & \nu_\mu N \to \mu^- \bar{D}^\circ D^\circ X \\ (1-y)^2, & \bar{\nu}_\mu N \to \mu^+ D^- D^+ X \end{cases}, \qquad (4)$$

and the region of variation of η and z is defined by the inequalities:

$$1+\Delta \leqslant \eta \leqslant \frac{1}{x} - \delta, \quad \eta - 2 + \frac{\epsilon}{\eta-1} \leqslant z \leqslant \text{for } 1+\Delta \leqslant \eta \leqslant 2; \ \epsilon \leqslant z \leqslant \eta - 2 + \frac{\epsilon}{\eta-1} \quad \text{for} \quad 2 \leqslant \eta \leqslant \frac{1}{x} - \delta \qquad (5)$$

In formulas (3) and (5) the quantities Δ, δ, $\epsilon \ll 1$ are defined by the equations:

$$\Delta = m_D(m_D + 2m_c)/2MExy, \quad \delta = m_c^2/2MExy, \quad \epsilon = m_D^2/2MExy, \qquad (6)$$

where M, m_D, m_c are the masses of the nucleon, D meson and c quark. In the derivation of Eq. (3) the D meson was assumed to be a point, contributions of the order of m_d^2/ME, m_c^2/ME were discarded, and the constant, standing at the peak of the transition $u(d)\to\bar{D}^\circ(D^-)c$, is denoted by $\sqrt{\gamma}$ and γ must be determined from an experiment.

If in Eq. (3) $\eta\to 1$ (with the condition that $\eta-1\gg\epsilon+\Delta$) and $z\sim 1$, then the first term gives the largest contribution. It corresponds to the usual "parton" contribution to $\sigma[\nu_\mu(\bar{\nu}_\mu)N\to\mu^-(\mu^+)X]$ with the subsequent fragmentation $u(d)$ $\bar{D}^\circ$ $(\bar{D}^-)c$, and the fragmentation function obtained is proportional to $\eta-2-z$, which, taking into account that $\eta\to 1$ and $z=-|z|$, agrees with the fragmentation function $D(|z|)\sim(1-|z|)^n$, (where $n=1,2$), usually used to describe the $\mu^-\mu^+$ events. For $\eta\sim 1$, $z\sim\epsilon$ the "nonparton" contribution, which is not described by the method given above, dominates in Eq. (3). However, in the calculation of the cross section of the processes (1), (2) it leads to a no less important contribution than the "parton". Integrating the differential cross section (3) with respect to z and η in the region (5) with Eqs. (6) taken into consideration, we obtain

$$\frac{d\sigma}{dxdy}=\left(\frac{G^2ME}{\pi}\right)\frac{\gamma}{64\pi^2}\Big[u(x)+d(x)\Big]\Bigg\{2xF(y)\ \ln\frac{[2MEy(1-x)-m_c^2]}{m_D(m_D+2m_c)}$$

$$+2x(1-x)(1-y)\ln\frac{2MExy}{m_D^2x}+[2x(1-y)\pm y(2-y)]x\ln x+(1-x)$$

$$\times[1-y-x(y-2)^2]\Bigg\}, \qquad (7)$$

where $F(y)$ is defined the same as in (4), and the region of applicability of Eq. (7) is defined by the inequalities:

$$xy>>m_D^2/2ME,\ (1-x)y>>(m_D+m_c)^2/2ME, \qquad (8)$$

following from the fact that the logarithmic expressions in (7) must be much larger than unity.

We obtain the x, y distributions using Eq. (7) and the parametrization of the $\mu(x)$, $d(x)$ functions from Ref. 13. In the numerical integration we take $x\geqslant 0.1$ in view of the fact that in the region $x<0.1$ the diffraction mechanism, considered in Ref. 14, dominates while its contribution can be ignored for $x\geqslant 0.1$. Figures 2 and 3 show the x, y distributions in region (8), averaged over the spectrum CDHS (for $\langle E\rangle\approx 50$ GeV). With the aid of these distributions we find:

$$\langle x\rangle_\nu=0.24;\ \langle y\rangle_\nu=0.71;\ \langle x\rangle_{\bar{\nu}}=0.21;\ \langle y\rangle_{\bar{\nu}}=0.59 \qquad (9)$$

The corresponding experimental values for 3μ events are equal to [2]:

$$\langle x\rangle_\nu=0.21\pm 0.02;\ \langle y\rangle_\nu=0.69\pm 0.02, \qquad (10)$$

and it follows from the histograms given in Ref. 1 for $\mu^\mp\mu^\mp$ events that

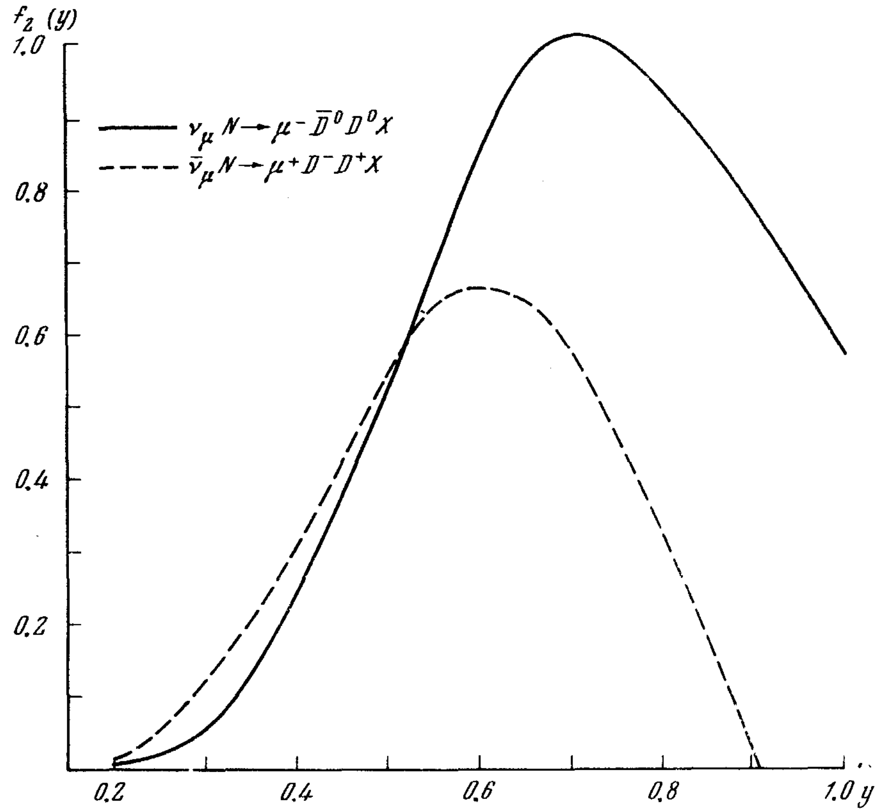

FIG. 3. Dependence of the quantity $f_2(y) = (d\sigma/dy)/[(G^2ME/\pi)\,\gamma/64\pi^2]$ on the variable y for processes (1) and (2).

$$\langle x\rangle_\nu = 0{,}28 \pm 0{,}15;\ \langle y\rangle_\nu = 0{,}59 \pm 0{,}22;\ \langle x\rangle_{\bar{\nu}} = 0{,}21 \pm 0{,}17;$$
$$\langle y\rangle_{\bar{\nu}} = 0{,}45 \pm 0{,}31. \tag{11}$$

We see that within the error limits our results (9) are identical to the experimental values (10), (11).

Using the graphs in Figs. 2 and 3, we obtain the total cross sections of the processes (1) and (2) in the form:

$$\sigma(\nu_\mu N \to \mu^- \bar{D}^0 D^0 X) = \left(\frac{G^2 ME}{\pi}\right)\frac{\gamma \cdot 0.47}{64\pi^2};\ \sigma(\bar{\nu}_\mu N \to \mu^+ D^- D^+ X) = \left(\frac{G^2 ME}{\pi}\right)\frac{\gamma \cdot 0.25}{64\pi^2} \tag{12}$$

We find γ from the data on singly charged dimuons[1,3] in $\nu_\mu N$ scattering. Taking into consideration Eq. (12), the data of Ref. 15 for $\sigma(\nu_\mu N \to \mu^- X)$, the experimental values

$R^{\nu}_{\mu\mu} = (3 \pm 2)\times 10^{-4}$ (from Ref. 1), $R^{\nu}_{\mu\mu} = (4 \pm 3)\times 10^{-4}$ (from Ref. 3), the generally accepted branching $B(\bar{D}^{\circ}\to\mu^{-} + ...)\approx 0.1$ and assuming that the contribution to $R^{\nu}_{\mu\mu}$ from D, $\bar{D}$ and D^{*}, $\bar{D}^{*}$ is approximately identical, we obtain the weighted average γ from the data of Refs. 1, 3 in the form

$$\gamma = 1.1 \pm 0.8. \tag{13}$$

This γ value makes it possible to estimate the quantities $R^{\bar{\nu}}_{\mu\mu}$, $R^{\nu}_{3\mu}$, $R^{\bar{\nu}}_{3\mu}$, predicted by the mechanism being considered. Taking Eqs. (12) and the data from Ref. 15 on $\sigma(\bar{\nu}_{\mu}N\to\mu^{+}X)$ into consideration, we obtain

$$R^{\bar{\nu}}_{\mu\mu} = (2.0 \pm 1.4)\cdot 10^{-4}; R^{\nu}_{3\mu} = (2.0 \pm 1.4)\cdot 10^{5}; R^{\bar{\nu}}_{3\mu} = (2.2 \pm 0.9)\cdot 10^{-5} \tag{14}$$

It follows from Eq. (14) that the predicted $R^{\nu}_{3\mu}$ agrees with the estimate for trimuons of nonelectromagnetic nature, made in Ref. 2 and given above.

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