Lepton spectrum for dimuons of the same sign in a neutrino-nucleon interaction

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(Submitted 14 November 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 5, 230–234 (10 March 1984)

The energy distribution of the slow muon is derived for a quasiparton mechanism for the case in which dimuons of the same sign are produced in a $\nu_\mu N$ collision. The ratio of the energies of the fast and slow muons according to this mechanism is compared with experimental data.

We now have many pieces of experimental evidence[1–5] to show that dimuons of the same sign (singly charged dimuons) are produced in $\nu_\mu N$ collisions. A so-called quasiparton mechanism has been proposed[6] to explain the nature of the $\mu^-\mu^-$ events in $\nu_\mu N$ interactions. This mechanism can be summarized by saying that the strongly virtual u quark, which is produced in the parton subprocess $\nu_\mu d \to \mu_1^- u$ (μ_1^- is the fast muon), emits a gluon which gives us a c, $\bar{c}$ pair. A final-state interaction then has the virtual u and $\bar{c}$ quarks recombing into a $\bar{D}^0$ ($\bar{D}^{*0}$) meson; as a result, a pair of charmed particles is produced in a reaction $\nu_\mu N \to \mu_1^- \bar{D}^0(\bar{D}^{*0})c + \ldots$. If the c quark converts into hadrons, and the $\bar{D}^0$ decays through a semilepton channel, $\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X$ (X is some hadron state, and μ_2^- is the slow muon), then we would have a $\mu^-\mu^-$ event. In the case $c \to \mu^+ + \ldots$, there would be a 3μ event. From the results in the literature we can conclude that none of the other suggested mechanisms is capable of explaining the nature of the singly charged dimuons.[7] It thus becomes extremely important to test the predictions of this mechanism.

An important characteristic of singly charged dimuons is the energy distribution of the slow muon, μ_2^-. In the present letter we derive the lepton spectrum for the

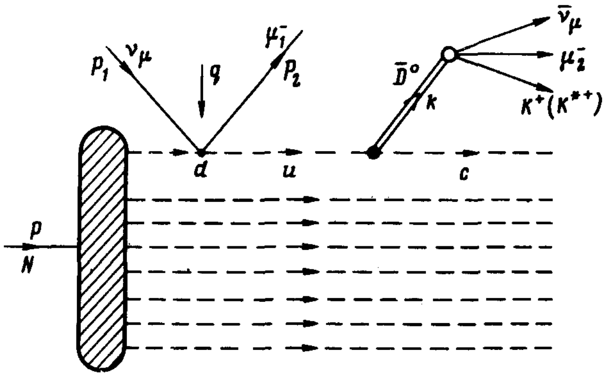

FIG. 1. A representative diagram of process (1).

reaction

$$\nu_\mu + N \to \mu_1^- + \mu_2^- + \ldots \tag{1}$$

Figure 1 shows an example of the diagrams which describe the amplitude for this process and also explains the notation used below for the 4-momenta. Let us state the assumptions under which we will derive the lepton spectrum. As was shown in Refs. 9 and 10, the width of the decay $\bar{D}_0 \to \mu_2^- \bar{\nu}_\mu X$ is dominated by the states $X = K^+, K^{*+}$, and we can quite accurately assume $\Gamma(\bar{D}_0 \to \mu_2^- \bar{\nu}_\mu K^+) \approx \Gamma(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu K^{*+})$ and ignore the effect of the hadron form factor on the probability for these decays. Furthermore, in view of the long lifetime of $\bar{D}^0$, it is natural to assume that its decay occurs from a real state (Fig. 1). We can thus write the lepton spectrum for μ_2^- in the reaction (1) in the following form:

$$\frac{d\sigma(\mu_1^- \mu_2^-)}{dz} = 4B\,(c \to \text{hadrons})\; B(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X) \int d\tau_{\bar{D}^0}$$

$$\times \frac{d\sigma(\nu_\mu N \to \mu_1^- \bar{D}^0 c + \ldots)}{d\tau_{\bar{D}^0}} \frac{dW\,(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X)}{dz}\,. \tag{2}$$

Here $B\,(c \to \text{hadrons}) \approx 90\%$ and $B\,(\bar{D}_0 \to \mu_2^- \bar{\nu}_\mu X) \approx 5\%$ are the standard branching ratios of the decays indicated in parentheses; $d\tau_{\bar{D}^0}$ is the phase space in the reaction $\nu_\mu N \to \mu_1^- \bar{D}^0 c + \ldots$; $z = E_{\mu_2^-}/(E_h + E_{\mu_2^-})$, where $E_{\mu_2^-}$ and E_h are the energies of the slow muon and of the final hadrons in the laboratory frame of reference; $dW(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X)/dz$ is the probability density of the semileptonic decay of the $\bar{D}^0$ meson; and the factor of 4 arises from the production of the $\bar{D}^{*0}$ meson in the reaction $\nu_\mu N \to \mu_1^- \bar{D}^{*0} c + \ldots$ in accordance with the yield ratio[6,7] $\bar{D}^{*0}{:}\bar{D}^0 = 3{:}1$. Under our assumptions we can then write $dW(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X)/dz$ as

$$\frac{dW(\bar{D}^0 \to \mu_2^- \bar{\nu}_\mu X)}{dz} = C\frac{G^2 E^5}{(2\pi)^3} y^5 \left(1 - \frac{\xi}{\eta - 2}\right) z^2 \left\{ z - \frac{3m_D^2}{8\omega}\left(1 - \frac{4m_K^2}{3m_D^2}\right)\right.$$

$$\left. - \frac{(3m_{K^*}^4 - 2m_K^4)}{16\,z\omega^2} - \frac{m_{K^*}^6}{8z\omega^2(m_D^2 - 4z\omega)} - \frac{[m_D^2(3m_{K^*}^4 - 2m_K^4) + 2m_{K^*}^6]}{64\,z^2\omega^3} \ln\left(\frac{4z\omega}{m_D^2} - 1\right)\right\}, \tag{3}$$

where

$$\omega = (Ey)^2 \left(1 - \frac{\xi}{\eta - 2}\right), \quad y = 1 - E_{\mu_2^-}/E, \quad \eta = -\frac{\tilde{q}^2}{2p\tilde{q}} \quad (\tilde{q} = q - k), \quad \xi = (E_{\bar{D}^0}/E_u)\eta - 1$$

($E_{\bar{D}^0}$ and E_u are the energies of the $\bar{D}^0$ meson and the u quark in the Breit frame of reference), E is the energy of the initial neutrino, $G = 10^{-5}\,M^{-2}$ (M is the nucleon mass), and the constant C is determined from the condition for the normalization of (2) to the total cross section $\sigma(\mu_1^-\,\mu_2^-)$. It was shown in Ref. 6 that $d\tau_{\bar{D}^0}$ can be expressed in terms of the variables $x = -q^2/2pq$, y, η, and ξ; and an expression was derived for $d\sigma(\nu_\mu N \to \mu_1^- \bar{D}^0 c + \ldots)$:

$$\frac{d\sigma(\nu_\mu N \to \bar{\mu}_1 \bar{D}^0 c + \ldots)}{dx\,dy\,d\eta\,d\xi} = \left(\frac{G^2 ME}{\pi}\right)\gamma \frac{x[u(\eta x) + d(\eta x)]\mathrm{sign}(\eta - 2)}{32\pi^2(\eta - 2)^2\eta^2}$$

$$\times\left\{\frac{2\eta^2}{(\eta - 1)}(\eta - 2 - \xi) + \frac{(\eta - 2)^2(1 - y)}{(\xi - 2\epsilon/\eta)} + \xi\eta^2(1 - y) - (\eta - 2 - \xi)[y(2 - y)\eta + y^2 + 6(1 - y)]\right\}, \tag{4}$$

where $\epsilon = m_D^2/(2MExy)$, and the constant γ, which is related to the constant g_P at the vertex of the transition $u \to \bar{D}^0 c$ by the relation $\gamma = g_P^2$, is[7] $\gamma = 1.0 \pm 0.2$.

To obtain the lepton spectrum we must carry out the integration over x, y, η, ξ at a fixed z in (2). It is simple to show, with the help of the results of Ref. 6, that the variable ξ lies in the range $\epsilon \leqslant \xi \leqslant (\eta - 2)(1 - m_D^2 z)/(m_D^2 - m_{K^*}^2)$. We will consider only the region $0.05 \leqslant z \leqslant 0.6$, since $d\sigma(\mu_1^- \mu_2^-)/dz$ is vanishingly small outside this region. Taking into account the threshold conditions in the parton subprocess $\nu_\mu d \to \bar{\mu}_1 \bar{D}^0 c$ involving the light quark and in the entire process $\nu_\mu N \to \mu_1^- \bar{D}^0 c + \ldots$ involving the nucleon, we find, for $z \lesssim 0.2$,

$$1 + \Delta \leqslant \eta \leqslant \frac{1}{x} - \delta;\ \frac{2m_D(m_D + M)}{ME} \leqslant y(1 - x)$$

$$\leqslant \frac{(1 - \kappa)}{2ME}\left\{\frac{(m_D + m_c)^2(1 - \kappa)}{z^2} + \frac{m_D(m_D + 2M)}{(1 - \kappa - z)}\right\}. \tag{5}$$

In the case $z > 0.2$ we have

$$1 + \Delta \leqslant \eta \leqslant 1 + \Delta\left(\frac{1 - \kappa}{z}\right)^2;\ \frac{(1 - \kappa)}{2ME}\left\{\frac{(m_D + m_c)^2(1 - \kappa)}{z^2}\right.$$

$$\left. + \frac{m_D(m_D + 2M)}{(1 - \kappa - z)}\right\} \leqslant y(1 - x) \leqslant \frac{2m_D(m_D + M)}{ME}\left(\frac{1 - \kappa}{z}\right)^2, \tag{6}$$

where

$$\Delta = \frac{(m_D + m_c)^2}{2MExy};\ \delta = \frac{m_D(m_D + 2M)}{2MExy(1 - z/(1 - \kappa))};\ \kappa = m_{K^*}^2/m_D^2.$$

In addition to threshold restrictions (5) and (6) we must consider the condition for the applicability of Eq. (4) which is set by the discarding of the terms containing m_D^2:

$$y \geqslant m_D^2/(2MEx), \tag{7}$$

We must also consider the kinematic cutoff in the experiments of Refs. 1–5: $E_{\mu_1^-}, E_{\mu_2^-} > E_\mu^{\min}$ (below we use $E_\mu^{\min} = 4.5$ GeV), which gives us the restrictions

$$y \geqslant \frac{E_\mu^{min}}{Ez};\ y \leqslant 1 - \frac{E_\mu^{min}}{E}. \tag{8}$$

Using (2)–(4), integrating over the intersection of regions (5)–(8), and dividing by $\sigma(\mu^-) \equiv \sigma(\nu_\mu N \to \mu^- X) = (0.414 \pm 0.020)(G^2 ME/\pi)$ at[11] $E = 95$ GeV (for convenience in comparison with other mechanisms), we find the lepton spectrum which we have

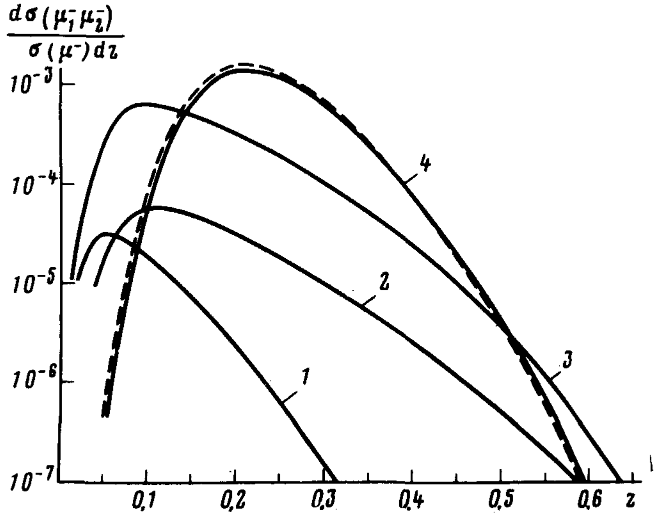

FIG. 2. The lepton spectrum for the slow muon, μ_2^-, in reaction (1). 1—Perturbative quantum chromodynamics mechanism[10]; 2, 3—mechanisms based on the transition[12] $\nu_\mu\bar{c}\to\mu^-\bar{b}$ with $(c,b)_L$ and $(c,b)_R$ coupling, respectively; 4—quasiparton mechanism.

been seeking (Fig. 2). It follows from conditions (7) and (8) that expression (4) holds only if $x \geqslant m_D^2/2M(E - E_\mu^{\min})$, while for comparison with experiment we must carry out the integration over all x in (2). We must accordingly approximate our results in the region $x\to 0$; the effect is to create an ambiguity in the lepton spectrum. The solid curve in Fig. 2 corresponds to the approximation that $d\sigma(\mu_1^-\mu_2^-)/\sigma(\mu^-)dxdz$ is a constant, while the dashed curve corresponds to the approximation of a straight line with a constant slope. Unfortunately, no experimental data are presently available on the lepton spectra for the slow muons in $\mu^-\mu^-$ events. We will accordingly compare our results with the predictions of other mechanisms.[10] From Fig. 2 we see that the perturbative quantum chromodynamics mechanism [in addition to predicting a value of $R^\nu_{\mu^-\mu^-} = \sigma(\nu_\mu N\to\mu^-\mu^- + ...)/\sigma(\mu^-)$ which is two orders of magnitude smaller than the experimental value] corresponds to too soft a spectrum, since the probability for the emission of a hard gluon drops sharply with increasing z. Mechanisms based on an analysis of the subprocess[12] $\nu_\mu\bar{c}\to\mu^-\bar{b}$ lead to a harder spectrum. For $(c,b)_L$ coupling, however, $R^\nu_{\mu^-\mu^-}$ is an order of magnitude below the experimental value, and the case with $(c,b)_R$ coupling is unattractive because it is based on a five-quark model, which is at odds with data on the branching ratios of the decay[13] $B\to\mu^-\mu^+X$ and leads to a vector-like coupling in the neutral currents. The lepton spectrum obtained from our mechanism (a quantum chromodynamics mechanism with nonperturbative effects) is quite hard, and after an integration over z it leads to the value $R^\nu_{\mu^-\mu^-} = (2.1 \pm 0.5)\times 10^{-4}$ (where the error stems primarily from[7] $\gamma = 1.0 \pm 0.2$), in good agreement with the average value over all the data of Refs. 1–5, $R^\nu_{\mu^-\mu^-} = (3.0 \pm 0.8)\times 10^{-4}$. If we multiply our value of $R^\nu_{\mu^-\mu^-}$ by the ratio of the standard branching ratios, $B(c\to\mu^+)/B$ $(c\to\text{hadrons}) = 1/9$, we find $R^\nu_{3\mu} = \sigma(\nu_\mu N\to\mu^-\mu^-\mu^+ + ...)/\sigma(\mu^-) = (2.3 \pm 0.5)\times 10^{-5}$; the experiment of Ref. 8

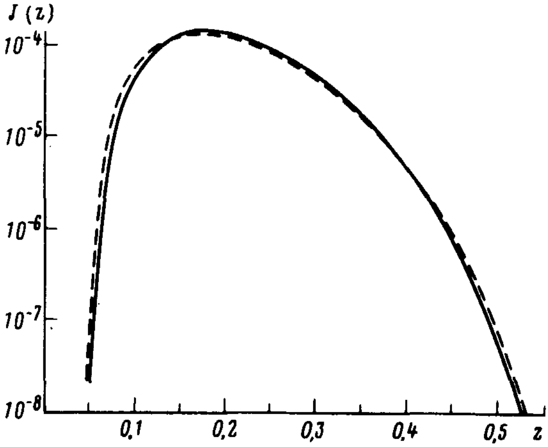

FIG. 3. The quantity $J(z)$ (explained in the text proper), required for the calculation of $\langle yz \rangle$, as a function of the energy of the slow muon.

yields $R^{\nu}_{3\mu} = (2.2 \pm 0.4) \times 10^{-5}$ for nonelectromagnetic 3μ events. The quasiparton mechanism thus describes $\mu^-\mu^-$ events and trimuons of hadron origin in a common approach as a consequence of an associated production of charm. Finally, we find the ratio $\langle E_{\mu_1^-} \rangle / \langle E_{\mu_2^-} \rangle = (1 - \langle y \rangle)/\langle yz \rangle$. To calculate $\langle yz \rangle$ we consider the function $J(z)$, which is found, by analogy with the lepton spectrum, by replacing y^5 by $y^6 z$ in (3). Figure 3 shows curves for $J(z)$ corresponding to these two approximations in the region $x \to 0$. Using these curves and the value[6] $\langle y \rangle = 0.66$, we find $\langle E_{\mu_1^-} \rangle / \langle E_{\mu_2^-} \rangle = (3.1 \pm 0.05)$ for our mechanism; the error corresponds to the ambiguity of the approximation at small values of x. The experiment of Ref. 3 yields $\langle E_{\mu_1^-} \rangle = 31.9$ GeV and $\langle E_{\mu_2^-} \rangle = 10.6$ GeV, i.e., $\langle E_{\mu_1^-} \rangle / \langle E_{\mu_2^-} \rangle = 3.009$. We see that the ratio of the energies of the fast and slow muons derived by the quasiparton mechanism agrees well with experiment.

I am deeply indebted to A. A. Ansel'm for useful discussions.

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Translated by Dave Parsons
Edited by S. J. Amoretty