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Dimuons Produced by Antineutrinos*

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In a run with a predominantly $\bar{\nu}$ beam we have observed seven dimuon events which show clearly that dimuons are produced by $\bar{\nu}$ as well as by ν. Using the signature of those events we tentatively identify twelve dimuon events from earlier runs as $\bar{\nu}$-induced. The characteristics of the total sample support the explanation that dimuons arise from new hadron production.

In previous papers[1,2] we have reported the observation of neutrino-induced dimuon events. The most probable explanation of the observed properties of these dimuons involves the production and subsequent weak decay of one or more new hadrons (Y particles) with mass in the region 2 to 4 GeV/c^2 and lifetime much less than 10^{-8} sec.[3,4] The Y particles necessarily possess a new, as yet unidentified, quantum number conserved by the strong and electromagnetic interactions, but not conserved by the weak interaction.

The dimuons observed thus far were produced by mixed neutrino-antineutrino beams in which the neutrino component was predominant.[1,2] As a consequence it was not possible to ascertain unequivocally from those data whether dimuons were produced by antineutrinos as well as by neutrinos. Since this is clearly an issue of considerable importance in the interpretation of dimuons, we have carried out an experiment at Fermilab in which the antineutrino component of the incident beam was made significantly larger than the neutrino component by the use of a double-magnetic-horn hadron focusing system in conjunction with a beam plug.[5] The results of that experiment are presented here.

The calculated fluxes of ν and $\bar{\nu}$ for two-horn hadron focusing with an absorptive beam plus are shown in Fig. 1(a), where it is seen that the $\bar{\nu}$ flux is expected to be roughly an order of magnitude larger than the ν flux in the energy region 30 to 100 GeV. These calculated spectra are confirmed by the measured energy spectra of single-muon events produced by the inelastic scattering of $\bar{\nu}$ and ν in the same beam. The observed ratio of single-μ^+ to single-μ^- events is about 10.

The brief run ($\sim 2\times 10^{17}$ protons on target) on which this experiment is based yielded a total of seven dimuon events, of which five had muon pairs of opposite charge (+/−) and two had muon pairs of the same charge (+/+). Furthermore, in four of the five (+/−) events the momentum of the positive muon p_+ was significantly larger than that of the negative muon p_- [see Fig. 2(a)]. This is in severe contrast to the dimuons reported previously,[1-3] among which p_+ was observed to be greater than p_- for only twelve events out of a total of 65 (+/−) events, and there were three (+/+) events and seven (−/−) events. Hence the data from the latest ($\bar{\nu}$) run, despite their low

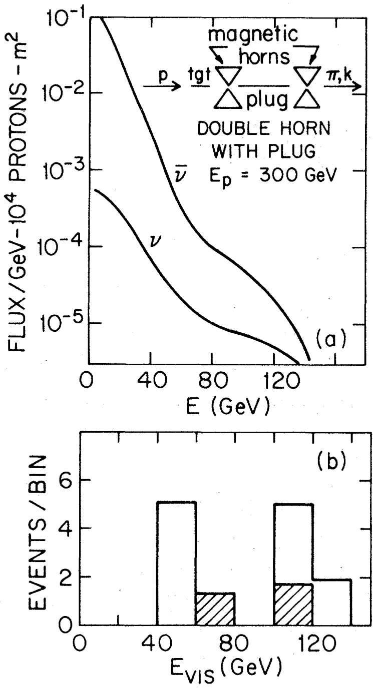

FIG. 1. (a) Calculated $\bar{\nu}$ and ν spectra for the double-horn $\bar{\nu}$ beam with an absorptive plug based on measured yields of pions and kaons. (b) Corrected distribution in E_{vis}. Events obtained during the $\bar{\nu}$ run are cross-hatched.

statistical significance, indicate unambiguously that dimuon events are indeed produced by $\bar{\nu}$, and that the signature of such events is $p_+ > p_-$.

The clarity of the dimuon signal from the predominantly $\bar{\nu}$ run suggests that the twelve dimuon events with $p_+ > p_-$ observed earlier might be identified as $\bar{\nu}$-induced. This assumption allows the formation of a sizable sample of $\bar{\nu}$-induced dimuons in which the contamination of ν-induced events is probably less than the statistical uncertainty of the sample. In the presentations of data that follow, the events from the $\bar{\nu}$ run are specially indicated.[6]

Figure 1(b) shows the distribution of events in E_{vis}, where the total visible energy $E_{\mathrm{vis}} = E_H + E_+ + E_-$ and E_H is the measured hadronic energy. No events are seen below 40 GeV even though the antineutrino flux below 40 GeV is appreciably higher than that above 40 GeV in the $\bar{\nu}$ run. This is the primary reason for the low dimuon yield in the $\bar{\nu}$ run [see Fig. 1(a)]. The data of Fig. 1(b) are compatible with a threshold for dimuon production near 30 GeV as reported earlier.[1] Above this threshold the event rate roughly agrees with a cross section rising linearly with energy.

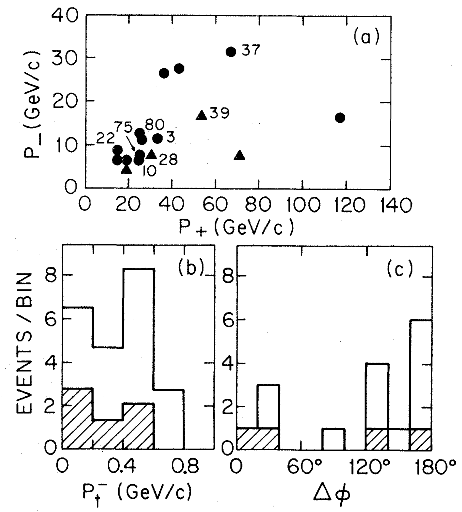

FIG. 2. (a) Scatter plot of p_+ versus p_- of all dimuon events with $p_+ > p_-$. The triangles signify events from the $\bar{\nu}$ run and the numbers are values of E_H in GeV associated with calorimeter events. (b) Distribution in the projected transverse momentum P_t^- of the negative muon. (c) Distribution in the azimuthal angle, $\Delta\varphi$, between the two muons in each dimuon event.

The measured ratio of $\bar{\nu}$-induced dimuons to $\bar{\nu}$-induced single muons, $\sigma_{\mu\mu}(\bar{\nu})/\sigma_\mu(\bar{\nu})$, for the restricted sample obtained in the $\bar{\nu}$ run is consistent with that for the complete sample within the large statistical errors. For the complete sample we find $\sigma_{\mu\mu}(\bar{\nu})/\sigma_\mu(\bar{\nu}) = (2 \pm 1)\times 10^{-2}$. Hence, taking[7] $\sigma_\mu(\bar{\nu})/\sigma_\mu(\nu) = \frac{1}{3}$, we obtain[2] $\sigma_{\mu\mu}(\bar{\nu})/\sigma_{\mu\mu}(\nu) = 0.8 \pm 0.6$, which does not distinguish between a dimuon cross-section ratio of unity or $\frac{1}{3}$.

Figure 2(a) shows a scatter plot of p_+ versus p_- for the sixteen events with $p_+ > p_-$. For these events the ratio $\langle p_-\rangle/\langle p_+\rangle = 0.35 \pm 0.08$, while for the restricted sample of four events obtained with the $\bar{\nu}$ beam $\langle p_-\rangle/\langle p_+\rangle = 0.24 \pm 0.09$. These values should be compared with the result $\langle p_-\rangle/\langle p_+\rangle = 6.1 \pm 0.8$ reported previously[2,3] for 42 events with $p_- > p_+$ obtained with a beam with substantially higher flux of neutrinos than antineutrinos.

Figure 2(b) shows the distribution of projected transverse momentum p_t^- of the μ^- with respect to the plane formed by the incident $\bar{\nu}$ and the μ^+. The distribution cuts off at $p_t^- \approx 1$ GeV/c as did the distribution in p_t^+ for the previous dimuon sample.[2,3] Figure 2(c) presents the distribution in the azimuthal angle $\Delta\varphi$ between the μ^+ and μ^- momentum vectors projected on a plane normal to the incident $\bar{\nu}$ direction. There is a tendency for the two muons to appear on opposite sides of the $\bar{\nu}$ beam, as would be expected if one of the

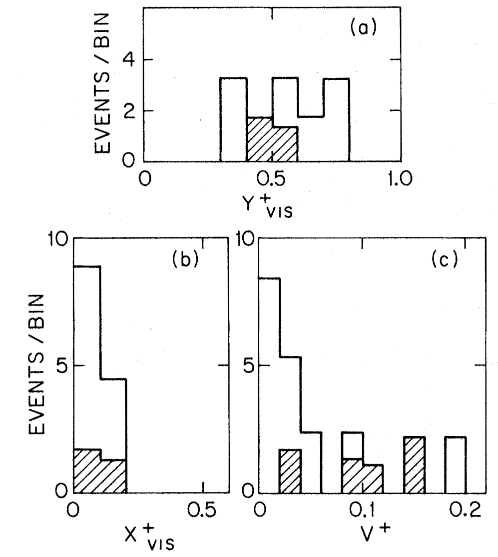

FIG. 3. Distributions in (a) y_{vis}^+, (b) x_{vis}^+, and (c) v^+. Events obtained during the $\bar{\nu}$ double-horn run are cross-hatched.

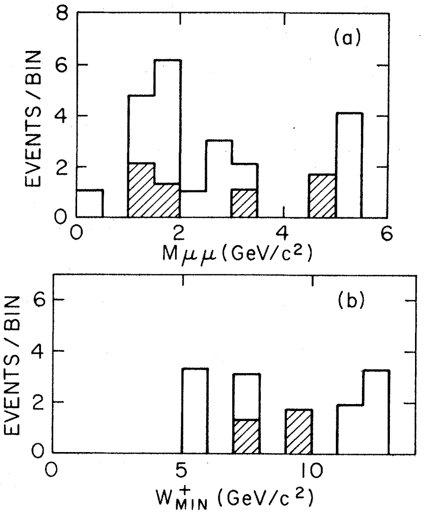

FIG. 4. (a) Distribution in the dimuon invariant mass $M_{\mu\mu}$. (b) Distribution in W_{min}^+, the minimum mass recoiling against the μ^+.

muons arose from the decay of a hadron of mass not more than a few GeV/c^2.

If the μ^- arises from the weak decay of a hadron, it is appropriate to consider the variables $y_{\mathrm{vis}}^+ = (E_{\mathrm{vis}} - E_+)/E_{\mathrm{vis}}$, $v^+ = 2(E_+/m)\sin^2(\theta_+/2)$, and $x_{\mathrm{vis}}^+ = v^+/y_{\mathrm{vis}}^+$. The $\bar{\nu}$ from the decay of the hadron will carry off unobserved energy and thus y_{vis}^+ and x_{vis}^+ are the lower and upper limits, respectively, of the Bjorken scaling variables y and x. Distributions in y_{vis}^+, x_{vis}^+, and v^+ are shown in Fig. 3. The v^+ distribution is consistent with that observed for deep inelastic antineutrino single-muon events. The distributions in x_{vis}^+ and y_{vis}^+ exhibit a strong similarity to the distributions in x_{vis}^- and y_{vis}^- and ν-induced dimuons, and show that the events occur at low x_{vis}^+ and relatively high y_{vis}^+, suggesting a connection with the anomalous flat y distribution observed at small x in $\bar{\nu}$-induced single-muon data.[8]

Figure 4(a) shows the observed corrected distribution in dimuon invariant mass $M_{\mu\mu}$ and Fig. 4(b) gives the distribution in W_{min}^+, the minimum total mass recoiling against the positive muon. These distributions are consistent with the observed distributions for $M_{\mu\mu}$ and W_{min}^- for neutrino production of dimuons.[3]

In summary, dimuon production by $\bar{\nu}$ has been observed with a rate relative to dimuon production by ν of 0.8 ± 0.6. The characteristics of these $\bar{\nu}$-induced dimuons are consistent with an interpretation in which the μ^- (and an unobserved $\bar{\nu}_\mu$) come from the decay of a new hadron, the antiparticle ($\bar{Y}$) of the Y particle necessary to explain ν-induced dimuons. The distributions in p_t^+ and W_{min}^+ support an estimate of the mass of $\bar{Y}$ in the region 2 to 4 GeV/c^2, the same as that of Y. Furthermore, the distributions in x_{vis}^+, y_{vis}^+, and v^+ strongly suggest a connection between the $\bar{\nu}$-induced dimuons and the previous observation[8] of an anomalous y distribution at low x for single-μ^+ production by $\bar{\nu}$. This connection is through the leptonic (or semileptonic) and hadronic weak decay modes of $\bar{Y}$, with the former yielding dimuons at about 0.1 the rate at which the latter gives rise to single muons. Both event types exhibit anomalously large y values for production by $\bar{\nu}$. In this interpretation, the energy threshold for dimuon production and the apparent scale-invariance violation in single-μ^+ production ($E_{\bar{\nu}} \gtrsim 30$ GeV) are also explained, as is the apparent charge-symmetry-invariance violation in single-μ^+ production.[8]

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[3] A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1203 (1975).

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[5] B. Aubert *et al.*, Colloq. Int. CNRS 245, 385 (1975).

[6] We have not included three events from the $\bar{\nu}$ run: the (+/-) event with $p_+ = 22.5 \pm 1.6$ and $p_- = 45.7 \pm 15.8$; and two (+/+) events with 12.1 ± 0.3, 7.8 ± 1.4, and 8.1 ± 0.2, 17.3 ± 0.8, all in GeV/c. All these events occur in iron.

[7] A. Benvenuti *et al.*, Phys. Rev. Lett. 32, 125 (1974), and in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975); B. Barish *et al.*, *ibid.*

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$\mu^+\mu^-$ Distributions from the Production of a New Hadron in Neutrino Scattering

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We have analyzed dimuon distributions due to the diffractive production of a new hadronic vector boson in neutrino scattering. Characteristic features that distinguish this mechanism from heavy-lepton-mediated dimuon distributions are presented.

Observed dimuon characteristics[1] in neutrino-induced reactions are not compatible with the events being mediated by heavy leptons.[2] The more probable source is the production of hadrons with new quantum numbers. However, the attendant dimuon characteristics will be dependent upon the details of the production mechanisms, which are unknown at the moment. To appreciate the kinds of characteristics expected from such reactions, one must appeal to models. If the new hadron can carry spin 1, then the diffractive mechanism would play an important role. In this note we examine dimuon distributions due to the diffractive production of a new vector hadron, F^{*+}. Specifically, we consider

$$\nu(k) + N(p) \rightarrow \mu^-(k_-) + F^{*+}(f) + X(p_x) \tag{1a}$$

$$\hookrightarrow \mu^+(k_+) + X' + \nu(k'). \tag{1b}$$

We shall only be concerned with dimuon distributions, in this initial analysis of hadron-mediated dimuon events, which are largely independent of the details of the model for (1a), and are basically controlled by the kinematics of hadron production. Thus we shall not discriminate among currently popular hadron spectroscopic schemes, nor shall we specify quantitatively the precise coupling strength of the hadrons, all of which information can only be forthcoming with further analysis of the data. For definiteness in the following discussion, we assume a mass, M_F, of 3 GeV/c^2 for the F^*, although our results are insensitive to variation in M_F for $M_F < 5$ GeV/c^2.

Although the precise way in which the semiweak diffractive scattering occurs is yet unclear, the following features may be deduced from photoelectroproduction of ρ mesons.[3] Firstly, there is a pronounced peak in the square of the momentum transfer, $t = (p - p_x)^2$, from the nucleon to the hadrons, with a width $1/b$. This means that the recoil hadrons get very little energy in the laboratory frame. Secondly, s-channel helicity conservation apparently holds; finally, diffractive dissociation of the target gives a distribution in recoil hadronic mass of the form $f(M_x^2) \sim 1/M_x^2$ for fixed t. We shall assume that all these features persist in Reaction (1). The inclusive cross section for (1a) will be controlled by the structure function

$$W_{\mu\alpha;\nu\beta} \sim \sum\nolimits_x \langle N|J_\nu^+|X; F_\beta^{*+}\rangle \langle X; F_\alpha^{*+}|J_\mu|N\rangle \delta^4(q + p - f - X), \tag{2}$$