Coherent Production of π^+ and π^- Mesons by Charged-Current Interactions of Neutrinos and Antineutrinos on Neon Nuclei at the Fermilab Tevatron

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Coherent single-pion production on neon nuclei is studied using the Fermilab 15-ft bubble chamber filled with a heavy Ne-H_2 mixture and exposed to the Tevatron neutrino beam. In the neutrino energy range 40–300 GeV, the net signal is 20 ± 6 events, giving a corrected rate per charged-current event of $(0.26 \pm 0.10)\%$. The cross section and kinematic distributions agree with the predictions of a model based on partial conservation of axial-vector current and meson dominance.

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Over the last few years, a consistent picture has been emerging from a series of experimental studies on single-pion coherent production by neutrinos.[1-8] The data are well described by the process illustrated in Fig. 1 (inset).[9-12] The pion in the final state is produced by the coherent scattering off the nucleus of the longitudinal component of the axial-vector field, dominated by the $J^{PC}=1^{++}$ a_1 resonance. At $Q^2=0$, the partial conservation of the axial-vector current (PCAC) hypothesis leads to Adler's result that this field couples to the W boson with the pin decay constant f_π. Away from $Q^2=0$, the cross section includes an a_1 propagator term. The energy domain studied so far ranges from 2 to 100 GeV.[13] The present experiment extends this range.

The coherent reactions

$$\nu_\mu + \text{Ne} \rightarrow \mu^- + \pi^+ + \text{Ne} \tag{1a}$$

and

$$\bar{\nu}_\mu + \text{Ne} \rightarrow \mu^+ + \pi^- + \text{Ne} \tag{1b}$$

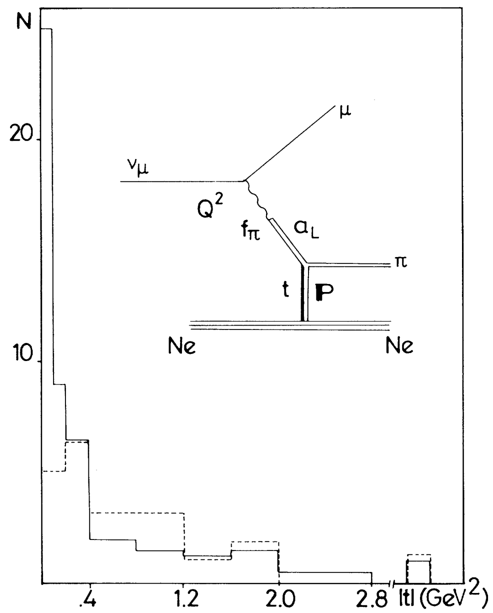

FIG. 1. Distributions of the square of the four-momentum transfer $|t|$ for 81 events with no stub (solid histogram) and for 24 events with stubs (dashed histogram), normalized to the former for $|t| > 0.1$ GeV^2. Inset: Coherent pion production by a charged-current neutrino interaction on a nucleus.

are studied at energies up to 300 GeV. The data were obtained in a four-month-long exposure of the 15-ft bubble chamber during the first neutrino Tevatron run. A quadrupole triplet beam containing $\frac{2}{3}$ neutrinos and $\frac{1}{3}$ antineutrinos was used. The average energies of the charged-current events were, respectively, 150 and 110 GeV. The chamber was filled with a heavy (76 mole% on the average) Ne-H_2 mixture. It was equipped with a new external muon identifier (EMI), and an internal picket fence (IPF).[14]

The data used here come from 132000 frames, corresponding to 2.3×10^{17} protons on target; this in turn corresponds to 14700 charged-current ν interactions and 2700 charged-current $\bar{\nu}$ interactions. The film was scanned for all neutral-particle–induced interactions. Measured were all two-prong events, i.e., events with two charged outgoing particles, with or without additional short heavy ionizing tracks ("stubs") due to slow protons or nuclear fragments,[15] and with or without associated γ or V^0. In addition, an inclusive sample of 10% of the events with all multiplicities was measured for normalization.

For the present analysis, we select two-prong events that satisfy the following requirements: (1) There is no associated γ or V^0; (2) both tracks have fractional momentum error $\Delta p/p < 0.7$; (3) one prong is identified as a muon by the IPF and two planes of the EMI, and has momentum $p_\mu > 10$ GeV; and (4) the other prong has opposite charge to the muon, and is not identified as a proton by range or ionization—it is assumed to be a pion. The analysis concentrates on the events with a total visible energy $E > 40$ GeV, where the contribution of this experiment is most significant.

A total of 105 $\mu\pi$ events with $E > 40$ GeV and $p_\mu > 10$ GeV was selected, including 24 events with a muon, a pion, and one or more stubs; the stubs are not used to compute the kinematical quantities of the event. There are 92 $\mu^-\pi^+$ events and 13 $\mu^+\pi^-$ events.

The coherent signal is obtained by comparing the $|t|$ distributions for the events with and without stubs. Here $|t|$ is given by

$$|t| = \Big(\sum_{\mu,\pi} E_i - p_i^L\Big)^2 + \Big(\sum_{\mu,\pi} \mathbf{p}_i^T\Big)^2, \qquad (2)$$

where E_i is the energy and p_i^L ($\mathbf{p}_i^T$) is the longitudinal (transverse) momentum of the muon or the pion, relative to the neutrino direction. For coherent events, the nucleus recoils as a whole without being detected in the bubble chamber, and $|t|$ is an excellent approximation to the square of the four-momentum transferred to the nucleus. Events with stubs are all noncoherent, while events without stubs may be a mixture of coherent and noncoherent events.

As observed in Fig. 1, the $|t|$ distribution of the events without stubs is characterized by a peak at small $|t|$ values. A similar peak is not seen in the $|t|$ distribution of the events with stubs. There are 25 (2) events without (with) stubs for $|t| < 0.1$ GeV^2, while there are 56 (22) such events for $|t| > 0.1$ GeV^2. Among the 25 events with no stub, 21 are $\mu^-\pi^+$ events and 4 are $\mu^+\pi^-$ events. The excess of events with no stub at $|t| < 0.1$ GeV^2 is attributed to coherent interactions. The background is estimated by normalizing the $|t|$ distribution for events with stubs to the distribution for events without stubs for $|t| > 0.1$ GeV^2, as done in Fig. 1. For $E > 40$ GeV, the coherent signal is thus evaluated to be 19.9 ± 6.3 events. The signal will be compared below to predictions based on PCAC and the meson-dominance model,[10–12] in a way similar to Refs. 4 and 8.[16] The necessary Monte Carlo simulation has been performed incorporating the model and taking into account the specific smearing conditions of the present experiment (separately for muons and pions).

To evaluate the absolute cross section, the signal of 19.9 ± 6.3 coherent events has to be corrected for several factors.

(a) The detection efficiency for $\mu\pi$ events is estimated to be 0.69 ± 0.16, on the basis of the results of a special scan performed on part of the data, using the EMI and the IPF to select frames with a muon originating in the bubble chamber.

(b) The correction factor for the discarded events where the charge and momentum of the muon or the pion are poorly evaluated ($\Delta p/p > 0.7$) is 1.16 ± 0.04.

(c) The correction factor for the cut at $|t| < 0.1$

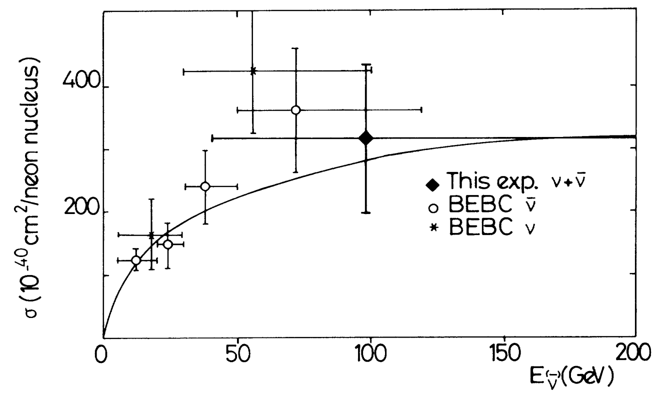

FIG. 2. Cross section for coherent pion production by ν and $\bar{\nu}$ interactions on neon, as a function of the energy E; the curve is the prediction of the model (Ref. 16) with the axial-vector mass taken as the a_1 mass. The full diamond represents data of this experiment. Symbols for data of Ref. 4 are the open circles, and the asterisks are for those of Ref. 8.

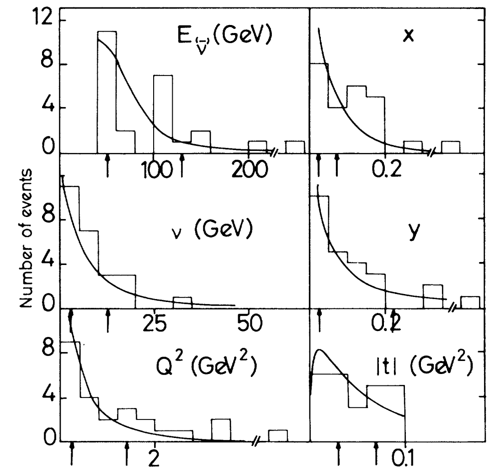

FIG. 3. Distributions of the kinematical variables for the 25 $\mu\pi$ events without stubs with $|t| < 0.1$ GeV^2; the positions of the two events with stubs and $|t| < 0.1$ GeV^2 are shown by the arrows. The curves, normalized to the 25 events with no stub, are the predictions of the model (Ref. 16).

GeV^2 is estimated to be 1.24 ± 0.04, using our Monte Carlo simulation. This rather large correction is mainly due to the smearing of the muon momentum ($\langle \Delta p/p \rangle = 0.10$ for $p_\mu > 10$ GeV), as the pion momenta are much smaller [cf. the distribution in $y = (E_\nu - E_\mu)/E_\nu = E_\pi/E_\nu$ in Fig. 3 below].

(d) According to the simulation, the loss of events due to the cut on the muon momentum at $p_\mu > 10$ GeV is negligible (less than 1%) for the coherent events with $E > 40$ GeV.

(e) Possible contamination of the coherent sample can come from neutral-current events, incident-neutral-hadron interactions, and coherent ρ and a_1 production. Each of these sources has been considered, and any contamination is found to be negligible.

The cross section for coherent interactions (1a) and (1b) in the Tevatron quadrupole triplet beam with $E > 40$ GeV is thus measured to be $(315 \pm 120) \times 10^{-40}$ cm^2 per neon nucleus, representing $(0.26 \pm 0.10)\%$ of all charged-current events with $E > 40$ GeV. This result is obtained using the total number of charged-current events, the beam composition and spectra, the known cross sections for neutrino and antineutrino charged-current interactions,[17] and the composition of the bubble-chamber liquid. This cross section is compared in Fig. 2 to data points from the Big European Bubble Chamber experiments at lower energies[4,8,18] and to the model predictions with the axial-vector mass taken as the a_1 mass: $m_a = 1.260$ GeV.[19] The model predicts equal cross sections for neutrinos and antineutrinos. For $E > 40$ GeV, we find the separate cross sections to be $(355 \pm 140) \times 10^{-40}$ cm^2 per nucleus for neutrinos, and $(215 \pm 120) \times 10^{-40}$ cm^2 per nucleus for antineutrinos. These cross sections are $(0.25 \pm 0.10)\%$ and $(0.36 \pm 0.19)\%$ of the ν and $\bar{\nu}$ charged-current cross sections, respectively.

If the above procedure is repeated for the energy range $10 < E < 60$ GeV, where most of the data from previous experiments lie, the coherent cross section is found to be $(285 \pm 150) \times 10^{-40}$ cm^2 per neon nucleus, in agreement with the earlier results. This cross section represents $(0.66 \pm 0.36)\%$ of all charged-current events with $10 < E < 60$ GeV.

The distributions of the kinematical variables E, $\nu = E - E_\mu$, Q^2 (the square of the four-momentum transfer from the leptons to the hadrons), $x = Q^2/2M_p\nu$ (M_p is the nucleon mass), $y = \nu/E$, and $|t|$ are shown in Fig. 3 for the 25 no-stub events with $|t| < 0.1$ GeV^2. The model predictions in the figure include the effects of the experimental smearing and cuts, and are normalized to 25 events. The positions of the two events with stubs and $|t| < 0.1$ GeV^2 are shown by the arrows. One observes a general agreement between the data and the predictions. The x and $|t|$ distributions appear flatter than expected, but are still compatible with the predictions within statistics.

To summarize, a study of reactions (1), the coherent production of π^+ and π^- mesons by charged-current interactions of neutrinos and antineutrinos on neon nuclei, has been performed in the 15-ft bubble chamber exposed to the Tevatron neutrino beam. The cross section and the distributions of the kinematical variables are in agreement with the predictions based on PCAC and the meson-dominance model. This measurement extends into the 100–300-GeV domain the consistent picture of single-pion coherent production which had emerged from several experiments performed at lower energies.

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[14]E632 Collaboration, V. Jain *et al.*, "Dimuon Production by Neutrinos in the Fermilab 15-ft. Bubble Chamber at the Tevatron" (to be published).

[15]A stub is a nuclear fragment or proton with momentum below 250 to 400 MeV; the momentum cut, evaluated at the scan table, varied with the depth of the event in the chamber. The stubs are not included in the event-prong count.

[16]See Refs. 8 and 13 for a detailed exposition of the model.

[17]The cross section for charged-current interactions is $[(72\pm4)$ and $(35\pm2)]\times10^{-40}E$ cm^2/GeV for ν and $\bar{\nu}$, respectively; see M. Aderholz *et al.*, Phys. Lett. **173B**, 211 (1986).

[18]As shown in Ref. 13, most other measurements at lower energies are also consistent with the model.

[19]$m_a=1.260$ GeV is the nominal a_1 mass from the Particle Data Group listing [G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988)]. When the value of m_a is taken to be 1.100 GeV, the predicted cross section is decreased by about 10%.