Diffractive Production of Vector Mesons in High-Energy Neutrino Interactions

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(Received 17 February 1978)

Results for diffractive production of vector mesons in high-energy neutrino-proton interactions are presented. Diffractive production of ρ^+ is observed with a cross section of $(8\pm3)\times10^{-40}$ cm^2 in agreement with recent theoretical predictions. Upper limits for A_1^+ and B^+ production are presented. The limit for B^+ production gives a new limit on the contribution of weak second-class currents.

Diffractive production of vector mesons provides a direct test of the relation between weak and electromagnetic currents; hence their presence or absence has important consequences. Recent calculations have predicted rates for these processes.[1] We have searched for vector-meson production in the following reactions: charged current (CC),

$$\nu p\to\pi^+\pi^+\pi^- p\mu^-, \qquad (1)$$

$$\nu p\to\pi^+\pi^0 p\mu^-, \qquad (2)$$

$$\nu p\to\pi^+\pi^+\pi^-\pi^0 p\mu^-; \qquad (3)$$

neutral current (NC),

$$\nu p\to\pi^+\pi^- p\nu, \qquad (4)$$

$$\nu p\to K^+K^- p\nu. \qquad (5)$$

The data come from two exposures of the Fermilab 15-ft bubble chamber, filled with hydrogen. The first (second) exposure of 70 000 (80 000) pictures was taken with a wide-band single-horn (two-horn) focused neutrino beam with primary proton energy of 300 GeV (400 GeV). With the higher beam intensity, the second exposure corresponds to ~75% of the data. The neutrino-event energy spectrum peaks at about 15 GeV, with ~90% of the spectrum below 100 GeV. Experimental details of the scanning, measurement, and reconstruction procedure will be given elsewhere.[2a] For the present analysis muons have been selected by a transverse-momentum algorithm rather than by the external muon identifier (EMI) due to limited geometric acceptance, and in the high-intensity running, the excessive hit rate in the EMI.

CC events were required to have the sum of the momenta in the beam direction (P_L) from the charged tracks at the production vertex greater than 7 GeV/c and a reconstructed neutrino energy greater than 10 GeV. For these events the muon was selected as the negatively charged noninteracting track with the highest transverse momentum relative to the total momentum of the other charged tracks. Cuts were also applied to reduce background from CC $\bar{\nu}$ and NC events.[2b] The NC events were selected as those with $P_L>4$ GeV/c where the negative track interacts or where the muon candidate lies on the same side of the beam as the component of the total momentum of the other charged tracks projected into the μ-ν plane.

Reaction (1) was obtained by a three-constraint (3-C) kinematic fit. Fits to this reaction with χ^2 probability > 5% were taken in preference to other fits obtained. Ambiguities between the π^- and μ^- assignments were resolved by selecting the μ^- as described above. The few remaining permutational ambiguities were resolved by selecting the fit with highest probability.

For the other reactions, one track had to be identified as a proton either by stopping or by having a significantly better helix-fit reconstruction as a proton than a pion.[3] Applying this test to protons identified by a 3-C fit to $\nu p\to\pi^+p\mu^-$ we find that the criteria select 0.79 ± 0.05 of protons with momentum $p_p<0.5$ GeV/c and 0.55 ± 0.5 for $0.5<p_p<1.0$ GeV/c, and select a wrong track in <1% of the events. Only identified protons with $p_p<1$ GeV/c were accepted.

With an identified proton and (for the CC events) an identified μ^-, candidates were selected for Reactions (2)–(5) as follows: Events with a 3-C fit to any reaction were rejected. Knowing the beam direction, the ν energy and the momentum of the missing neutral were calculated by a "0-

C fit" for the reactions listed. Events with $E_d > -0.02$ GeV were rejected, where $E_d = E_{out} - m_p - P_L$, with m_p the proton mass, and E_{out} and P_L the sum of the outgoing charged-particle energy and momentum in the beam direction, respectively. Perfectly measured events with no missing neutrals should have $E_d = 0$. The cut $|E_d| < 0.02$ GeV removes additional 3-C fit candidates since 90% of the 3-C events satisfy this cut. Those with $E_d > 0.02$ GeV indicate a wrong mass assignment. The samples obtained have a background of events with more than one missing neutral. Calculation of the 0-C solution of Reaction (2) for a class of "events" known to have two or more missing particles, namely the selected five-prong events with two charged pion tracks removed, indicates that such backgrounds will not produce narrow ($\lesssim 400$ MeV width) structures in the meson mass spectra studied.

All the invariant-mass combinations from the five reactions have been studied in detail. In particular, those in which a vector meson may be produced have been studied as a function of $t' = t - t_{min}$, where t is the momentum transfer from target proton to final proton. For Reactions (2)–(5), the proton identification procedure restricts $|t'| \lesssim 0.5$ GeV^2, the region appropriate for diffractive production. The results and theoretical predictions are summarized in Table I. The backgrounds quoted are estimated from the general shape of the distribution and Monte Carlo calculations. The signal or upper-limit results are corrected for scanning and reconstruction losses, proton identification, and, where applicable, unobserved decay modes of the resonance.[4] The results have been normalized to the corrected total number of charged-current events (~3000) and cross sections averaged over the flux distribution have been obtained with use of previous measurements.[6]

The mass distributions are shown in Fig. 1 and results for each reaction are discussed below:

(1) $\nu p \to \pi^+\pi^+\pi^- p\mu^-$.—A strong Δ^{++} signal is observed, and also an enhancement in the region of ρ^0 in the $\pi^+\pi^-$ mass distribution. The background in this region is reduced if we plot $\pi^+\pi^-$ mass only from those events with $\pi^+ p$ mass (containing the other π^+) in the Δ^{++} region, suggesting that we are observing the process $\nu p \to \rho^0\Delta^{++}\mu^-$. The $\pi^+\pi^+\pi^-$ mass distribution is mainly below 1.4 GeV. To study the diffractive production process a selection $|t'| < 0.5$ GeV^2 is made. If, in addition, one of the $\pi^+\pi^-$ mass combinations is required to

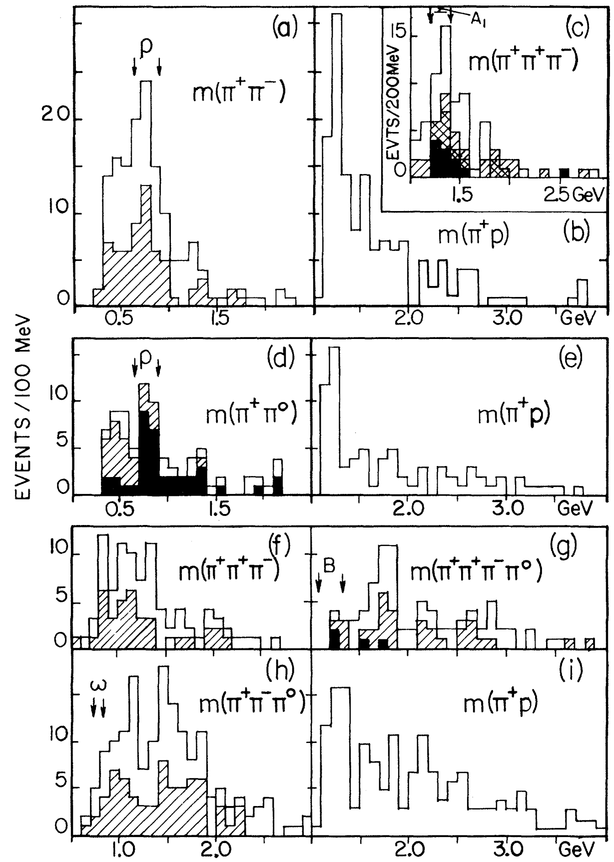

FIG. 1. Mass distributions (a)–(c) from Reaction 1 ($\nu p \to \pi^+\pi^+\pi^- p\mu^-$), (d) and (e) from Reaction 2 ($\nu p \to \pi^+\pi^0 p\mu^-$), and (f)–(i) from Reaction 3 ($\nu p \to \pi^+\pi^+\pi^-\pi^0 p\mu^-$). The hatched area in (a) is with the other π^+ in the Δ^{++} region. The hatched area in (c) is from events with $|t'| < 0.5$ GeV^2, the double-hatched area with the additional requirement that $m(\pi^+\pi^-)$ be in the ρ region and the solid area with the extra condition $Q^2 < 2$ GeV^2. The hatched areas in (d)–(h) are with $Q^2 < 2$ GeV^2. The solid area in (d) is with events with $m(\pi^+ p)$ in Δ^{++} removed, and in (g) with $m(\pi^+\pi^-\pi^0)$ in the ω region selected.

be in the ρ region, the 3π mass distribution is concentrated in the region 0.9 to 1.3 GeV. If events with $\pi^+ p$ in the Δ^{++} are removed only four of the thirteen events in this region remain. However, the total hadronic invariant mass W is low, peaking at ~2.5 GeV with only 15% above 5 GeV, and at the peak W the Δ^{++} band overlaps at least $\frac{1}{2}$ of the A_1 region of the $\rho^0\pi^+ p$ Dalitz plots. These reflection effects are confirmed by Monte Carlo studies, and have been taken into account in the upper limit given in Table I.

(2) $\nu p \to \pi^+\pi^0 p\mu^-$.—A strong Δ^{++} signal is seen in the $\pi^+ p$ mass distribution. In the $\pi^+\pi^0$ distribution an enhancement is observed in the ρ region.

TABLE I. Summary of results and theoretical predictions. Mass ranges were taken as Δ, 1.08–1.4; ρ, 0.65–0.9; ω, 0.73–0.83; B, 1.1–1.35; φ, 0.99–1.1; A_1, 0.9–1.3 GeV. Results are for all Q^2, but the selection $Q^2 < 2$ GeV^2 makes no significant reduction in the signal or limits. Predictions from Ref. 1b are for $Q^2 < 2$ GeV^2.

Reaction	Resonance	Number of events (raw data)	Estimated Background	Signal or 90% confidence upper-limit.[a] Fraction of total c.c.%	Cross section (10^{-40} cm^2)	Theoretical Predictions Cross sections[b] (10^{-40}cm^2) Ref. 1a	Ref. 1b	Ref. 1d
(1) $\nu p \to \pi^+\pi^+\pi^- p\mu^-$	$\Delta^{++} \to \pi^+ p$	64	16	2.1±.4	25±4			
(75 events all t')	$\rho^\circ \to \pi^+\pi^-$	52	38	.6±.3	7±3			
	$\Delta^{++}\ \rho^\circ$	25	13	.5±.2	6±3			
($\|t'\| < 0.5$ GeV^2)	$A_1 \to \rho^\circ \pi^+$	13	8	<.9	<11	2.5-3.5	{15 5	55
(2) $\nu p \to \pi^+\pi^\circ p\mu^-$ (82 events)	$\rho^+ \to \pi^+\pi^\circ$	16	3	.7±.2	8±3	5-9	14	24
(3) $\nu p \to \pi^+\pi^+\pi^-\pi^\circ p\mu^-$	$\omega \to \pi^+\pi^-\pi^\circ$	6	6	<.2	< 3			
(88 events)	$B^+ \to \pi^+\omega$	2	2	<.2	< 2	22-26	-	-
(4) $\nu p \to \pi^+\pi^- p\nu$ (33 events)	$\rho^\circ \to \pi^+\pi^-$	8	6	<.8	< 9	~ 0.8	0.5	.7
(5) $\nu p \to K^+K^- p\nu$ (13 events)	$\varphi \to K^+K^-$	0	0	<.7	< 7	-	0.2	.3

[a]See Ref. 4.

[b]See Ref. 5.

If events with $Q^2 > 2$ GeV^2 are removed the background is reduced. If, in addition, events with $\pi^+ p$ in the Δ^{++} are removed the low mass background is much reduced revealing a clear ρ^+ signal of thirteen events above an estimated background of three events.[7]

(3) $\nu p \to \pi^+\pi^+\pi^-\pi^0 p\mu^-$.—The only structure observed is a clear Δ^{++} signal. The $\pi^+\pi^-\pi^0$ mass resolution in the region ω is ~30 MeV but there is no ω signal, nor indication of B^+ decaying to $\pi^+\omega$. The accumulation of events in the region 1.70–1.90 GeV in the $\pi^+\pi^+\pi^-\pi^0$ distribution is consistent with the distribution obtained by a Monte Carlo model, assuming a transverse-momentum-limited phase-space distribution, with the observed fraction of Δ^{++} production and restricted t' distribution.

(4) $\nu p \to \pi^+\pi^- p\nu$ *and* (5) $\nu p \to K^+K^- p\nu$.—The events selected for these channels include a large background from hadronic and CC events.[8] However, there is no indication of structure in the $\pi^+\pi^-$ or K^+K^- mass distribution.

The observation of the process $\nu p \to \mu^-\rho^+ p$ provides the first test of conserved-vector-current hypothesis (CVC) away from $Q^2 = 0$. Our results are in good agreement with the predictions of Chen, Henyey, and Kane.[1a] However, Bartl, Fraas, and Majeratto[1b] and Gaillard, Jackson, and Nanopoulos[1d], using the simple vector-dominance-model Q^2 dependence, would predict ~40% of ρ^+ production with $Q^2 > 2$ GeV^2, whereas we observe that the ρ signal has $Q^2 < 2$ GeV^2. Further information on the correct Q^2 dependence can be obtained by examining the y distribution of these events, which is all below $y = 0.4$ and peaks at $y \sim 0.15$. Within limited statistics, the energy distribution of the ρ^+ events is consistent with an energy-independent cross section between 10 and 100 GeV.

The A_1^+ is supposed to play the same role for the axial-vector current as the ρ^+ does for the vector current; hence the observation of $\nu p \to \mu^- A_1^+ p$ would provide a crucial test. The upper limit obtained for this process is well above the predictions of Ref. 1a, but a factor of 5 below those of Ref. 1d. For NC reactions the upper limits presented are well above the predicted rates.

Production of the B^+ meson has been suggested as a test for second-class weak currents.[9] To interpret our result as a limit on second-class currents it is necessary to have a value for f_B, the coupling constant of the B to a second-class current. In Ref. 9 a model for f_B was given, introducing a factor K multiplying the second-class current term with $K = 1$ corresponding to universality with first-class currents. The authors use $K = 1$,[9] consistent with the nuclear results available at that time, to obtain the predicted cross sections given in Table I. Thus, within the assumptions of the model[9,1a] our results give a 90%-confidence-level upper limit for the parameter $K<0.3$. The latest nuclear experiments[10] expressed in terms of this parameter give a limit $K<0.1$; thus our result confirms the nuclear results using completely different model assumptions.

To summarize, we have observed diffractive production of ρ^+ as predicted by models applying CVC to electroproduction results.[1a] We are unable to isolate an A_1^+ signal because of reflection effects of Δ^{++}, but the limits we obtain are consistent with predictions.[1a,1b] From the nonobservation of B^+ production we obtain a limit on the strength of second-class weak currents, within the assumptions of the model of Refs. 9 and 1(a), comparable with the limits from latest nuclear experiments.[10]

This work was supported in part by the U. S. Department of Energy and the National Science Foundation.

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[2b]Events with $y<0.9$ or $R>3$ were removed, where R is the ratio of the maximum value of $(P_T P)$ for any positive charged track, to the value for the μ^- candidate, with P_T and P the transverse to beam and total momentum, respectively. See Ref. 2a for details.

[3]A nonstopping track was taken to be a proton if $r>1.45$ (1.30) for event processed through (TVGP) geometry, where r is the ratio of the pion to proton mass dependent helix-fit residuals.

[4]For all reactions except (1) a correction of 1/0.79 for proton identification efficiency was applied. For Reactions (4) and (5) a factor of 2.2 was used to correct for NC events excluded by the "same-side" criteria. Factors were applied to correct for losses due to poorly measured tracks (5% of three prongs, 11% of five prongs) and for losses in kinematic fitting for Reaction (1) (14%).

[5]The theoretical predictions have been evaluated by averaging over the neutrino energy spectrum from this experiment. A factor of 2 has been included in the predictions for each case from Ref. 1a are from their models (III) and (I), the two extreme cases.

[6]B. C. Barish et al., Phys. Rev. Lett. 39, 1595 (1977); D. C. Cundy, in Particles and Fields—1977, edited by G. H. Thomas, A. B. Wicklund, and P. Schreiner (American Institute of Physics, New York, to be published), was obtained with $\sigma_n/\sigma_p = 1.93 \pm 0.05$ as calculated using quark distribution of R. D. Field and R. P. Feynman, Phys. Rev. D 15, 2590 (1977).

[7]The CC muon selection for all events in the ρ signal has been confirmed by the EMI information.

[8]The separation of Reactions (4) and (5) was made only on the evaluation of E_d, thus all candidates for (5) are also candidates for (4).

[9]M. S. Chen, F. S. Henyey, and G. L. Kane, Nucl. Phys. B114, 147 (1976).

[10]See, for example, review by F. Calaprice, in Proceedings of the Fourth International Conference on Hyperfine Interactions, Madison, New Jersey, 13–17 June 1977 (to be published). The parameter $g_{II}/g_A \approx -7.7$ K (see Ref. 9).