Single-Pion Production in Neutrino and Antineutrino Reactions*

W. Lee, E. Maddry, P. Sokolsky, and L. Teig
Columbia University, New York, New York 10027

and

A. Bross, T. Chapin,† L. Holloway, L. Nodulman,‡ T. O'Halloran, and C. Y. Pang§
University of Illinois, Urbana, Illinois 61801

and

K. Goulianos and L. Litt‖
Rockefeller University, New York, New York 10021
(Received 29 September 1976)

We have studied the neutral-current reactions $\nu_\mu N \to \nu_\mu N'\pi^0$ and $\bar{\nu}_\mu N \to \bar{\nu}_\mu N'\pi^0$ and compared them to the charged-current reactions $\nu_\mu N \to \mu^- N''\pi^0$ and $\bar{\nu}_\mu N \to \mu^+ N''\pi^0$. We have measured the ratios $R_0' = \sigma(\nu_\mu N \to \nu_\mu N'\pi^0)/2\sigma(\nu_\mu N \to \mu^- N''\pi^0)$ and $\bar{R}_0' = \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu N'\pi^0)/2\sigma(\bar{\nu}_\mu N \to \mu^+ N''\pi^0)$ to be 0.17 ± 0.04 and 0.39 ± 0.18, respectively. We also present the $\pi^0 p$ invariant-mass distribution of the neutrino-induced reactions.

We report in this Letter the results of a study of the reactions

$$\nu n \to \nu n \pi^0, \quad \bar{\nu} n \to \bar{\nu} n \pi^0, \tag{1}$$

$$\nu p \to \nu p \pi^0, \quad \bar{\nu} p \to \bar{\nu} p \pi^0, \tag{2}$$

$$\nu n \to \mu^- p \pi^0, \quad \bar{\nu} p \to \mu^+ n \pi^0. \tag{3}$$

The existence of weak neutral currents has been known for several years. However, little is known about their properties. Single-pion production channels are among the simplest ν ($\bar{\nu}$) reactions. Thus, the study of cross sections and hadronic final states provides useful information about the structure of the weak neutral currents.[1] This experiment was performed in the fast-extracted, horn-focused, wide-band neutrino beam at the Brookhaven National Laboratory (BNL). Details of the beam and the experimental setup have been described earlier.[2]

This Letter is based on the analysis of 700 000 (300 000) pictures taken from the neutrino (antineutrino) run with an average proton beam intensity of 4.3×10^{12} (5.0×10^{12}) protons/pulse. The film was scanned to select events which were consistent with the reactions (1), (2), and (3). Candidates were measured and reconstructed in space with a 4-ft×4-ft fiducial cut on the vertex position. Ranges in the target material were then calculated. Reconstructed tracks were matched to counter hits so that the time of flight and pulse heights for the event could be determined. Since the target is composed of complex nuclei, events may also include tracks from nuclear breakup. We estimate that these tracks have a maximum range of 2 in. in aluminum. The following criteria are used to choose the final event sample: (1) An event can have a maximum of two tracks with a range exceeding 2 in. of aluminum. (2) Only one of these tracks can have a visible interaction. (3) Any number of short or nuclear-breakup tracks, each with a range less than 2 in. in aluminum, is accepted. (4) We require one or two electromagnetic showers with a minimum of 10 sparks each. Single showers must be associated with other tracks. (5) Events which originate in the range chambers are rejected.

In this experiment, a muon is defined to be a straight track with range greater than 2 interaction lengths (60% of events), a straight track which exits with minimum ionizing pulse height (28%), or a stopping track with visible multiple scattering (12%). A proton is an interacting track (15%), a stopping straight track (75%), or a straight exiting track with pulse height greater than 1.5 times that for minimum ionizing (10%). The pulse-height distribution of stopping straight tracks is consistent with that expected from stopping protons. A π^0 is one or two showers which can be extrapolated to the vertex. By definition, charged-current (CC) events can have one muon, one neutral pion, at most one proton, and any number of short tracks with range less than 2 in. Neutral-current (NC) events can have one neutral pion, at most one proton, and any number of short tracks. Using the above criteria, we have 204 (22) NC and 641 (35) CC candidates for neu-

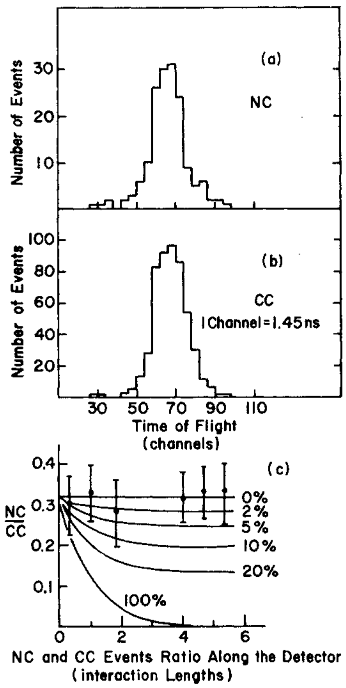

FIG. 1. (a) Time-of-flight distribution of NC events. (b) Time-of-flight distribution of CC events. (c) The ratio of NC to CC events along the detector. Curves correspond to the expected distribution with the indicated percentage of neutron contamination in NC events.

trino (antineutrino) reactions.

A possible source of background for the neutral-current events is single-pion production by neutrons. The detector subtends a small solid angle with respect to the muon shield and its center line is approximately 12 ft above ground. The small solid angle and the absence of nearby neutron sources reduce the neutron-induced background. There are, however, three ways to check for neutron-induced background. The time-of-flight distribution for NC events is similar to that for CC events [Figs. 1(a) and (b)] and shows no evidence for neutrons up to a momentum of 1.5 GeV/c from the nearest steel shield. Higher-energy neutrons cannot be separated by time of flight. However, the ratio of NC to CC events shows no evidence of attenuation along 5 interaction lengths of material in the detector [Fig. 1(c)]. The measured interaction length in our apparatus is 25 cm of aluminum. If the neutrons come from the sides, the direction of the πp system would be expected to point predominantly towards the center of the apparatus. The data show no evidence for this effect. We conclude that the contamination of the NC events by neutron-induced events is negligible.

In order to determine the ratios

$$R_0' = \frac{\sigma(\nu N \to \nu N' \pi^0)}{2\sigma(\nu N \to \mu^- N'' \pi^0)} \qquad (4)$$

and

$$\bar{R}_0' = \frac{\sigma(\bar{\nu} N \to \bar{\nu} N' \pi^0)}{2\sigma(\bar{\nu} N \to \mu^+ N'' \pi^0)}, \qquad (5)$$

where N, N', and N'' are target nuclear states (70% aluminum and 30% carbon), several corrections must be considered. CC events will be classified as NC events if the muon escapes detection. In order to estimate this correction, we have compared the observed muon angular distribution with the results of a Monte Carlo simulation based on a model of single-pion production by Adler.[3] We estimate that $(10 \pm 2)\%$ of the muons from the CC neutrino reaction escape detection in the detector. For antineutrino reactions, we estimate this effect to be less than 4%.

We also correct for the relative detection efficiency of NC and CC events, since NC events with a single shower and no visible vertex are not accepted. This correction was determined from the CC data by studying single-shower events with no visible proton or nuclear breakup. The detection efficiencies for Reactions (1) and (2) relative to Reaction (3) are 0.37 and 0.76, respectively. Another source of background is dipion production reactions in which the charged pion is misidentified as a proton. Using the higher-topology shower events, such as $\nu_\mu n \to \mu^- n \pi^+ \pi^0$ and asking how often the π^+ would be misidentified as a p, we estimate that this contamination is approximately 20% in CC and NC events. Hence, in calculating R_0' ($\bar{R}_0'$), we have made no correction for this effect.

We must also consider ν ($\bar{\nu}$) contamination in the $\bar{\nu}$ (ν) beam. Antineutrino contamination in the neutrino beam is estimated to be small. However, neutrino contamination in the antineutrino beam, coupled with the larger ν cross section, is not negligible. We studied this problem by comparing the quasielastic processes $\nu n \to \mu^- p$ and $\bar{\nu} p \to \mu^+ n$ observed in both beams. We estimate the neutrino contamination in the antineutrino beam to be 15%. We have incorporated this correction in calculating $\bar{R}_0'$. With the corrections discussed above and assuming the cross sections for Reactions (1) and (2) to be equal, we obtain $R_0' = 0.17 \pm 0.04$ and $\bar{R}_0' = 0.39 \pm 0.18$.

Because the target is not composed of free nucleons, the theoretical calculations of these ra-

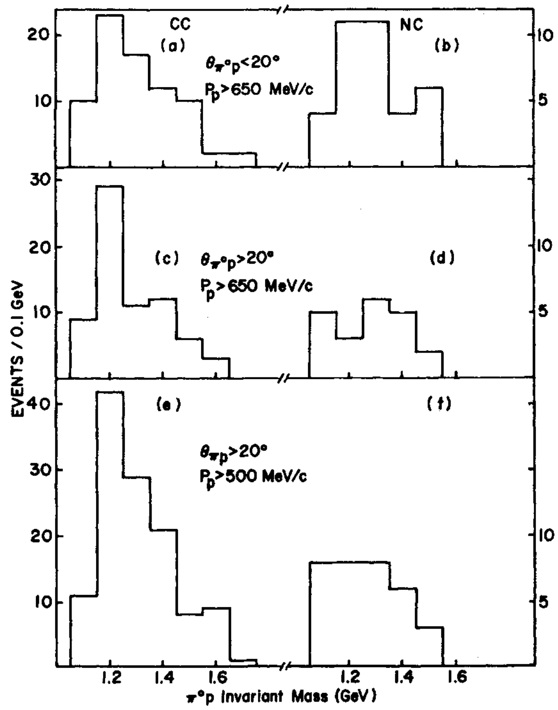

FIG. 2. Invariant-mass distributions of $\pi^0 p$ system. Vertical scales are number of events. The Δ enhancement in (b) is believed to be due to CC contamination.

tios must be corrected for charge-exchange effects. These effects have been calculated by Adler, Nussinov, and Paschos.[4] In the Weinberg-Salam model with $\sin^2\theta_W = 0.35$, they predict that $R_0' = 0.20$ and $R_0' = 0.25$, which is consistent with the observed ratios.

The $\pi^0 p$ invariant mass, which is sensitive to the isospin $I=\frac{3}{2}$ and $I=\frac{1}{2}$ amplitudes in the final state, can be calculated for ν-induced CC and NC events. The proton momentum can be found indirectly from the range in the target material. To determine the π^0 momentum, events with two visible showers are used to make a linear fit to the shower energy as a function of the number of sparks. The proportionality constant is found to be 11 ± 3 MeV per spark. Finally, we impose two cuts: (a) The proton must stop inside the detector with a momentum $\geqslant 650$ MeV/c and a polar angle $<80°$. The first cut reflects the fact that the momentum distribution of breakup and rescattered protons lies below 650 MeV/c, while the second is the kinematic limit for the proton. We also present distributions for $p_p > 500$ MeV/c. Note that broadening of the $\Delta(1236)$ mass peak is to be expected in this region. (b) The momentum of the π^0 must be greater than 250 MeV/c. This reduces the poor energy resolution inherent in low-energy showers. With these cuts, the mass resolution in our detector is ~ 0.1 GeV.

Since wide-angle muons are strongly correlated to forward $\pi^0 p$ production, the contamination of NC by CC events is much greater than 10% at small $\theta_{\pi^0 p}$. Figures 2(a) and 2(b) show the CC and NC mass distribution for $p_p > 650$ MeV/c and $\theta_{\pi^0 p} < 20°$. We expect this region to show strong CC contamination in the NC events, and the data are indeed consistent with Δ production both in the CC and NC data. Figures 2(c), 2(d), 2(e), and 2(f) show the CC and NC mass distributions for $\theta_{\pi^0 p} > 20°$ where rescattering and CC contamination are believed to be small. We observe that the CC events are dominated by $\Delta(1236)$ production but the NC events do not appear to have the same enhancement. However, more data are needed before we can draw a firm conclusion.

We wish to thank Steve Adler for his advice and encouragement throughout the duration of the experiment.

*Research supported by the National Science Foundation and the U. S. Energy Research and Development Administration.

†Present address: Rockefeller University, New York, N. Y. 10021.

‡Present address: University of California at Los Angeles, Los Angeles, Calif. 90024.

§Present address: Lawrence Berkeley Laboratory, University of California, Berkeley, Calif. 94720.

‖Present address: Michigan State University, East Lansing, Mich. 48823.

[1]W. Lee, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975); W. Lee *et al.*, Colloq. Int. CNRS 245, 205 (1975), and in Proceedings of International Neutrino Conference, Aachen, West Germany, June 1976 (to be published); S. J. Barish *et al.*, Phys. Rev. Lett. 33, 448 (1974); F. J. Hasert *et al.*, Phys. Lett. 59B, 485 (1975).

[2]W. Lee *et al.*, Phys. Rev. Lett. 37, 186 (1976).

[3]S. L. Adler, Phys. Rev. D 9, 229 (1974). We thank Professor Adler for providing us with his computer programs.

[4]Stephen L. Adler, Shmuel Nussinov, and E. A. Paschos, Phys. Rev. D 9, 2125 (1974).