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STUDY OF THE ISOSPIN PROPERTIES OF SINGLE-PION PRODUCTION BY NEUTRINOS*

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ABSTRACT

Results are presented on the three single-pion production reactions $\nu p \to \mu^- p \pi^+$, $\nu n \to \mu^- n \pi^+$, and $\nu n \to \mu^- p \pi^0$. Measurements were made from threshold to a neutrino energy of 1.5 GeV using the Argonne National Laboratory 12-foot bubble chamber filled with deuterium and exposed to a broad band neutrino beam. In addition to a resonant isospin $I = 3/2$ $N\pi$ amplitude, we find a large $I = 1/2$ amplitude as predicted by Adler.

We present updated (1) results on the study of the three weak charged current single pion production reactions

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

$$\nu d \to \mu^- n \pi^+ p_s \qquad (2)$$

$$\nu d \to \mu^- p \pi^0 p_s \qquad (3)$$

With the usual assumption that the weak charged current has a V,A spatial structure; detailed calculations have been made by S. Adler(2,3) for low mass N_π systems.

We have measured reaction (1) from threshold to a neutrino energy $E_\nu = 6$ GeV. Reactions (2) and (3) have a cut $E_\nu < 1.5$ GeV to minimize backgrounds from two-pion-production events (8±4% with this cut on neutrino energy). The study of these reactions allows one to measure the $I = 3/2$ N_π and $I = 1/2$ N_π amplitudes. Results of the study of the reaction $\nu p - \mu^- p \pi^+$ have been reported previously(4). Using the present data we can directly test the usual assumption that the weak charged current is pure isovector, and limits can be set on the magnitude of the isotensor contribution.

Our results are based on the analysis of 1,089,000 pictures taken in the Argonne 12-foot bubble chamber exposed to a broad band neutrino beam. The neutrino energy spectrum peaks at 0.5 GeV and has decreased by about an order of magnitude by 1.5 GeV(4).

The mean overall scanning efficiency was greater than 95%. We have double scanned more than three-fourths of the pictures used in this analysis. The events were measured and then processed through the TVGP-SQUAW geometrical reconstruction and kinematic fitting programs. The mean overall measuring efficiency was greater than 97%. Each event candidate was examined by a physicist who checked the results of the measurement and estimated the track ionization densities. See Ref. (1) for a discussion of the event selection procedure and background corrections. Table 1. lists the present rate corrections for reactions (1), (2) and (3).

Events are assigned to reaction (1) on the basis of a three constraint χ^2 probability greater than 1%. For reactions (2) and (3) the event assignment is in general unique. The positive track can be recognized as a proton or a pion on the basis of track, shape, ionization, or decay. In 7% of the events considered as candidates for reaction (2) or (3) the positive track remains ambiguous. These events are therefore weighted 1/2 in their assignment to reactions (2) and (3).

Fig. (1) shows the N_π mass spectrum for reactions (1), (2) and (3) respectively. The shaded events in Fig. (1a) are those which satisfy the energy cut imposed on reactions (2) and (3). The isospin of the final state hadrons in reaction (1) is 3/2 and Fig. (1a) shows nearly pure production of the Δ^{++} (1232), although phase space allows masses above 2 GeV. Figs. (1b) and (1c) show that Δ production still occurs; it does not dominate either channel. In particular, there is significantly greater production of high mass N_π systems in these two channels.

TABLE 1. RATE CORRECTIONS

REACTION	REASON	CORRECTION
$\nu d \to \mu^- p \pi^+ n_s$	Background Loss of fast neutron spectators	(5± 3)% (19± 4)%
$\nu d \to \mu^- n \pi^+ p_s$	Background Incoming charged tracks which scatter Loss of under-constrained events	(9.25±4.1)events (7± 3)% (8± 2)%
$\nu d \to \mu^- p \pi^0 p_s$	Background Events assigned to $\nu d \to \mu^- p p_s$ Loss of under-constrained events	(9.95±3.7)events (18± 5)% (4± 2)%

Fig. (2) shows the four-momentum transfer Q^2 distributions. Again the shaded events in Fig. (2a) are those which satisfy the energy cut of reactions (2) and (3). The shaded events in Fig. (2c) are those repopulated due to losses into the $\nu d \to \mu^- p p_s$ channel.

Fig. (3) shows the excitation function for the three reactions. The cross section for the $\mu^- p \pi^+$ final state (Fig. (3a)) given for E_ν up to 6 GeV exhibits a plateau between 1 and 1.5 GeV. Since the data for the other two reactions are cut off at a neutrino energy of 1.5 GeV, the expected turnover cannot be seen with the present statistical accuracy.

After making the appropriate rate corrections and background subtractions we find, for neutrino energies less than 1.5 GeV, the following number of events 368.4±29.7, 110.6±14.9 and 120.3±16.5 for reactions (1), (2) and (3) respectively.

In the region of Adler's calculation (2,3), ($N\pi$ masses below 1.4 GeV), we find the corresponding numbers 363.3±29.4, 94.0±12.8 and 105.7±14.3, respectively.

Assuming the $\Delta S = 0$ weak hadronic charged current transforms as an isovector plus a possible isotensor contribution we can write the amplitudes for reactions 1, 2 and 3 in terms of three reduced amplitudes which correspond to the I=1/2 and I=3/2 states of the $N\pi$ system. These amplitudes are

$$A(\pi^+ p)=A_3-(1/\sqrt{5})B_3 \qquad (4)$$

$$A(\pi^+ n)=\frac{1}{3}A_3+\frac{2}{3}A_1+(1/\sqrt{5})B_3 \qquad (5)$$

$$A(\pi^0 p)=(\sqrt{2}/3)A_3-(\sqrt{2}/3)A_1+\sqrt{2/5}B_3 \qquad (6)$$

where A_1 and A_3 are isovector exchange amplitudes and B_3 is the hypothetical isotensor exchange amplitude(5). If B_3 is zero then the amplitudes $A(\pi^+ p)$, $A(\pi^+ n)$ and $A(\pi^0 p)$ must satisfy a set of triangle inequalities. Moreover, if $B_3 = 0$, it is still possible with minimal assumptions to set an upper limit on $|B_3/A_3|$.

Assuming $I=3/2$ dominance ($A_3 >> A_1$) and $B_3 = 0$ we expect from eqs. (4), (5) and (6) that

$$R^{+} = \sigma(\mu^- n\pi^+)/\sigma(\mu^- p\pi^0) = \frac{1}{2} \qquad (7)$$

and

$$R^{++} = (\sigma(\mu^- n\pi^+) + \sigma(\mu^- p\pi^0)/\sigma(\mu^- p\pi^+) = \frac{1}{3} \qquad (8)$$

Experimentally we find (for $M(N\pi) < 1.4$ GeV), $R^{+}=0.89\pm0.17$ and $R^{++}=0.55\pm0.07$. These results imply the existence of at least an A_1 amplitude in addition to the A_3 amplitude.

Adler predicts(3) values of $R^{+}=0.76$ and $R^{++}=0.60$ in the basic model. In the extended model for weak pion production the Adler predictions(3) for (R^{+}, R^{++}) are (0.79,0.49) and (0.71,0.53) depending on the recipe used for modifying the Born approximations to conform to the soft pion limit. We see that the theoretical predictions are in agreement with the present experimental results. For comparison the theoretical area-normalized invariant mass and Q^2 distributions are shown on Figs. (1) and (2); the agreement in shape is seen to be reasonable.

If we assume that isotensor exchange is absent, i.e. $B_3 = 0$, we find that our data satisfy the resulting triangle inequalities. Consequently, $I=2$ exchange is not required by the data. Solving for the magnitudes of A_1 and A_3, as well as their relative phase φ for $M(N\pi) < 1.4$ GeV: we obtain $|A_1|/|A_3|=0.57\pm0.06$ and $\varphi = 89.2\pm8.7$ deg. These data are consistent with a resonant $I=3/2$ amplitude in the presence of a large nonresonant $I=1/2$ πN background.

Finally if we allow B_3 to be nonzero but require that it feed only the Δ (1232) resonance, as does A_3, then it must be real relative to A_3. One then finds the following relationship between the amplitudes:

$$\frac{(\sqrt{5} + 3\alpha)}{(\sqrt{5} - \alpha)} A(\pi^+ p) = A(\pi^+ n) + \sqrt{2} A(\pi^0 p), \quad (9)$$

where $\alpha = B_3/A_3$. The resulting triangle inequalities for the magnitudes are satisfied only if $-0.51\pm0.01 \le \frac{B_3}{A_3} \le 0.14\pm0.04$.

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Figure Captions

Figure 1.

Nucleon pion two-body effective masses for reactions (1), (2) and (3), respectively. The theoretical curves (Ref. 2,3) have been folded with the experimental N_π mass resolutions of ±25 MeV for (b) and ±40 MeV for (c). For (a) the shaded events are those which satisfy the energy cut applied to reactions (2) and (3).

Figure 2.

Four-momentum transfer squared $Q^2(\nu,\mu^-)$ distributions for events with $M(N_\pi) < 1.4$ GeV. For (a) the shaded events are those which satisfy the energy cut applied to reactions (2) and (3). For (c) the shaded events are those added to make up for losses into the $\mu^- pp_s$ channel. The curves are all from Ref. 2.

Figure 3.

Excitation function cross sections for reactions (1), (2) and (3), respectively. The errors include a 10% uncertainty in the flux normalization. Theoretical curves are not shown for (b) and (c) since the Adler model only describes N_π masses below 1.4 GeV. The theoretical curves in (a) (Ref. 3) are for two different cases as described in the text.

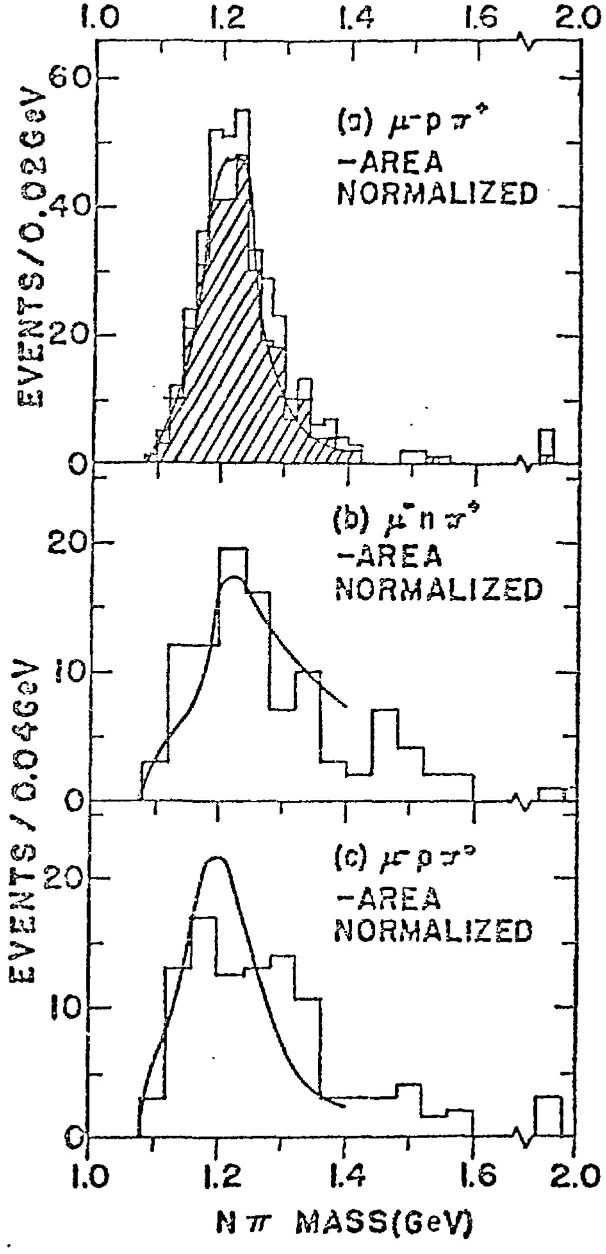

1.0
1.2
1.4
1.6
2.0
EVENTS/0.02GeV
60
40
20
0
(a) $\mu^- p \pi^+$
-AREA
NORMALIZED
(b) $\mu^- n \pi^+$
-AREA
NORMALIZED
EVENTS / 0.04GeV
20
10
0
(c) $\mu^- p \pi^0$
-AREA
NORMALIZED
20
10
0
1.0
1.2
1.4
1.6
2.0
N π MASS(GeV)

Fig. 1

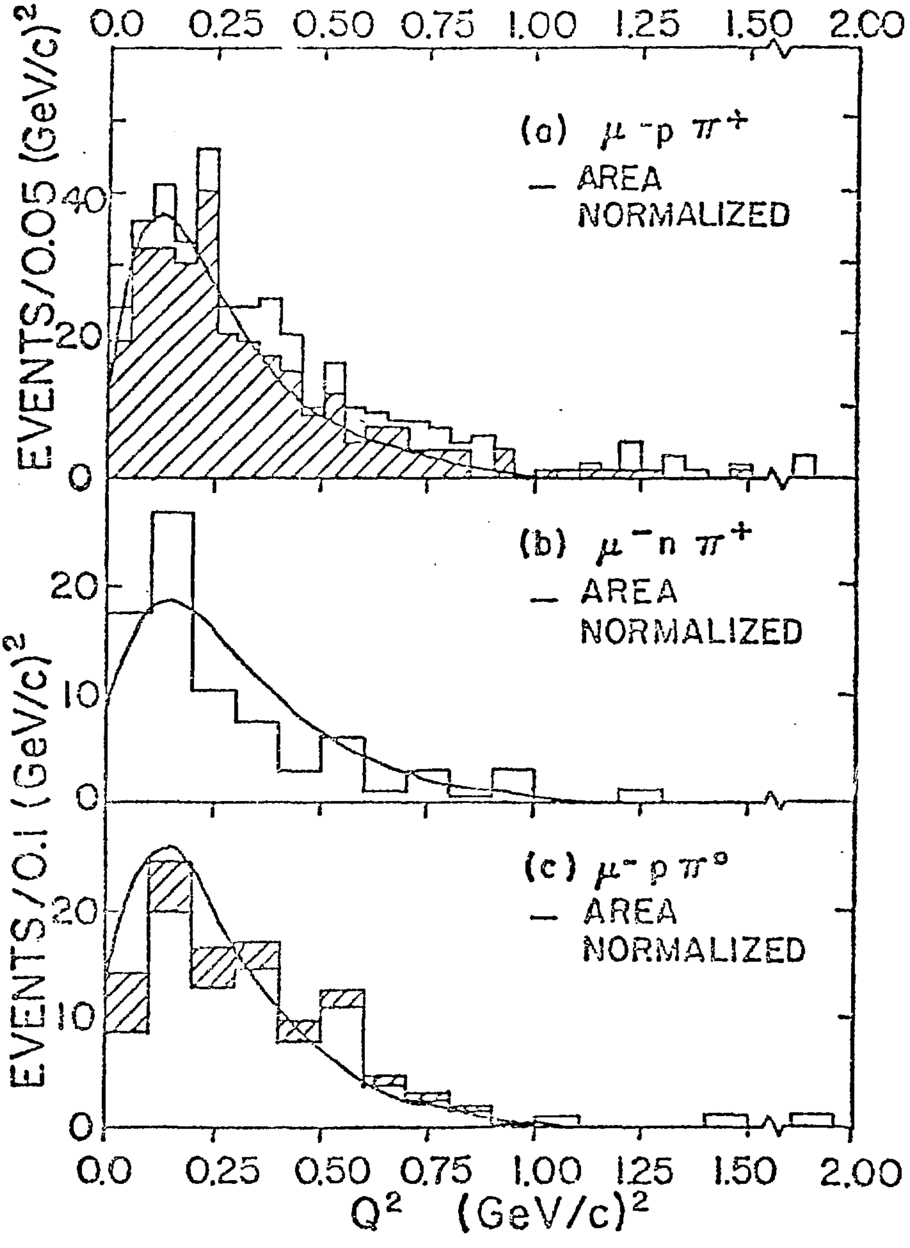
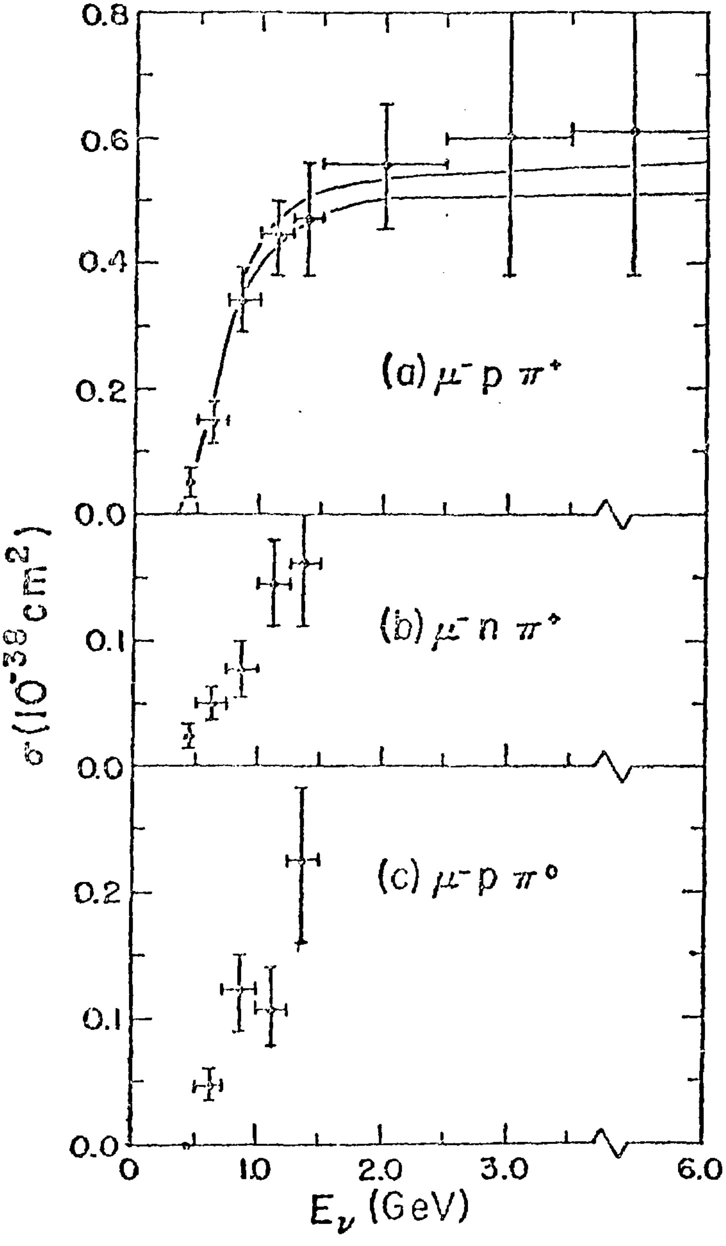

(a) $\mu^- p \pi^+$
— AREA NORMALIZED
(b) $\mu^- n \pi^+$
— AREA NORMALIZED
(c) $\mu^- p \pi^0$
— AREA NORMALIZED
EVENTS/0.05 (GeV/c)^2
EVENTS/0.1 (GeV/c)^2
0
20
40
0
10
20
0
10
20
0.0
0.25
0.50
0.75
1.00
1.25
1.50
2.00
Q^2 (GeV/c)^2

Fig. 2



0.8
0.6
0.4
0.2
0.0
(a) $\mu^- p \, \pi^+$
0.1
0.0
(b) $\mu^- n \, \pi^+$
0.2
0.1
0.0
(c) $\mu^- p \, \pi^0$
$\sigma \, (10^{-38} \mathrm{cm}^2)$
0
1.0
2.0
3.0
6.0
E_ν (GeV)

Fig. 3