use of Eqs. (4) and (5) will not cause much of an error. With this proviso all of the entries in Table III involve no new parameters. Tables II and III taken together give an extremely consistent picture based on the vector-dominance and SU(3) models particularly when it is remembered that theory columns should have errors of the order of 10–20% and do not explicitly take finite-width corrections into account.

In the analysis presented here the errors assigned to theory are only those arising from the coupling-constant determinations and do not include estimates of errors incurred by using vector dominance. The naive quark model predicts absolute values for radiative decays. To the extent that relative values of decays are considered it can be put into correspondence with the vector-dominance approach, the latter method allowing a reasonable estimate of error to be made. It is clear from the tables that most of the data will have to be known much more accurately than it is at present before a meaningful test is to be made. As an example, the $\rho^- \to \pi^-\gamma$ width of either[3] 35 ± 10 keV or a factor of 2 larger[12] can reasonably be accounted for by the result in Table II.

I should like to thank D. Ryan for an informative discussion on the experimental analysis of the Primakoff effect.

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[12]L. Strawczynski, Ph.D. thesis, University of Rochester, 1974 (unpublished), quotes the result of Ref. 3 in a weaker sense; $\Gamma_{min} < \Gamma(\rho \to \pi\gamma) < \Gamma_{max}$, where $\Gamma_{min} = 30 \pm 10$ keV and $\Gamma_{max} = 80 \pm 10$ keV because of lack of knowledge of the phase φ. The larger errors of Ref. 4 arise from a different way of accounting for the same problem (D. Ryan, private communication).

Study of the Isospin Properties of Single-Pion Production by Neutrinos*

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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-ft bubble chamber filled with hydrogen and deuterium and exposed to a broad-band neutrino beam. In addition to a resonant isopin $T = \frac{3}{2}$ πN amplitude, we find a large $T = \frac{1}{2}$ amplitude as predicted by Adler.

Single-pion production is one of the simplest reactions between neutrinos and hadrons. Within the framework of $V-A$ theory, detailed calculations have been made by Adler[1] for the production of low-mass π-nucleon systems in the charged-current reactions

$$\nu p \to \mu^- p\pi^+, \tag{1a}$$

$$\nu d \to \mu^- p\pi^+(n_s), \tag{1b}$$

$$\nu d \to \mu^- n\pi^+(p_s), \tag{2}$$

and

$$\nu d \to \mu^- p \pi^0 (p_s). \tag{3}$$

We have measured all these reactions from threshold to a neutrino energy of 1.5 GeV. Some of our results on Reaction (1) which measures the pure $T=\frac{3}{2}$ πN amplitude have been reported previously.[2] Study of Reactions (2) and (3) allows one to measure the $T=\frac{1}{2}$ amplitude as well. This paper is the first to give results on all three reactions from an experiment using a simple target. The usual assumption that the weak current is a pure isovector can be directly tested using these data, and limits can be set on the magnitude of the isotensor contribution.

Our results are based on the analysis of 945 000 pictures (580 000 D_2, 365 000 H_2) taken in the Argonne National Laboratory 12-ft 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.[2]

More than 80% of the film was double-scanned. The mean overall scanning efficiency was greater than 95%. The events were measured and then processed through the TVGP-SQUAW geometrical reconstruction and kinematic fitting programs. Each candidate was then examined by a physicist who checked the results of the measurement and estimated the track ionization densities. The selection of events for Reaction (1a) is completely straightforward since the only unknown quantity is the energy of the interacting neutrino, and so a three-constraint kinematic fit is performed. Reaction (1b) is complicated by the presence of the neutron spectator. We simulate the spectator distribution by constraining the neutron to have momentum components of 0 ± 50 MeV/c. However, events with high-momentum spectators are lost using this procedure and the correction is estimated to be $(9 \pm 2)\%$.[3]

The selection of events for Reactions (2) and (3) is substantially more difficult. Since each of these reactions leads in general to the production of an undetected neutral particle in the final state, the equations of energy and momentum balance are not overconstrained. We first separate off events that result in constrained fits by Reaction (1b) or by the quasielastic scattering reaction $\nu d \to \mu^- p(p_s)$, with χ^2 probability greater than 1%. Since events of Reaction (3) which have π^0 transverse momenta small compared to the neutrino beam momentum often are fitted by the quasielastic scattering hypothesis, they tend to be lost and a four-momentum transfer (Q) dependent correction of $(29 \pm 6)\%$ has been applied.[4]

A potential source of false events comes from charged pions which enter the chamber and scatter. False fits by Reaction (2) to this source characteristically force the outgoing neutron to be of high momentum and nearly parallel to the neutrino beam direction. By excluding events where the ratio of the computed neutron to neutrino momentum exceeds 0.9 and the laboratory angle between these momenta is less than 10° this background is substantially eliminated. In addition, since pion-nucleon elastic scattering typically occurs at small angles, we reject all events which have the μ^- momentum and the reversed pion momentum collinear within 30°. Using the $\mu^- p \pi^+$ sample, we find that the loss of events due to these cuts is 6%. Events from all three reactions are subjected to identical cuts in making cross-section comparisons.

A second source of background to Reactions (2) and (3) is due to double-pion production channels. We estimate this background from a study of the double-pion reactions $\nu d \to \mu^- \pi^+ \pi^- p(p_s)$, $\nu p \to \mu^- \pi^+ \pi^+ n$, and $\nu p \to \mu^- \pi^+ \pi^0 p$. The excitation function for such reactions rises steeply for neutrino energies greater than about 2 GeV.[5] Furthermore, if one ignores one of the charged pions and treats a real double-pion production event as a single-pion event, the resulting calculated neutrino energy tends to remain above 1.5 GeV. By considering only single-pion events of Reactions (2) and (3) with neutrino energy less than 1.5 GeV, the double-pion contamination is reduced to $(8 \pm 4)\%$. Finally, there is a small background due to neutrons and γ's of 0.7 ± 0.3 event in Reaction (2) and 1.7 ± 1 events in Reaction (3).[6]

In general, the assignment of events to one or the other of Reactions (2) and (3) is unique. The positive track can be recognized as a proton or a pion on the basis of track shape, ionization, or decay up to momenta of about 1 GeV/c. Approximately 5% of the events have positive tracks with momentum above 1 GeV/c and are therefore ambiguous. However, because the available energy in the c.m. system is small for our events so that the final-state nucleon generally carries most of the available momentum, we have classified these tracks as protons. Only about 9% of the pions in Reaction (1) have momenta greater than 500 MeV/c.

The full histogram in Fig. 1(a) shows the $p\pi^+$ mass spectrum from Reactions (1a) and (1b). The shaded events are those from Reaction (1b)

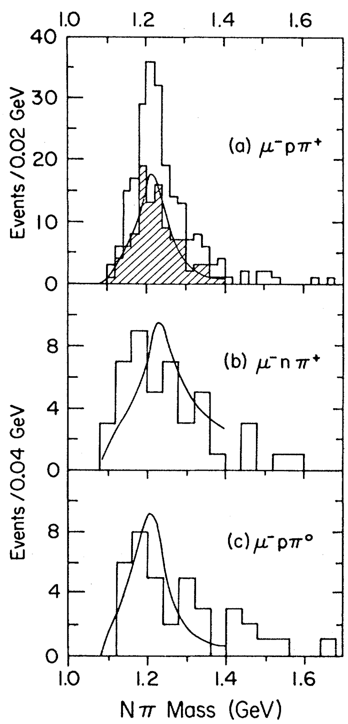

FIG. 1. Nucleon-pion two-body effective masses for Reactions (1)–(3). The curves are theoretical calculations due to Adler (see Ref. 1). The $N\pi$ mass resolutions are ± 6, ± 20, and ± 30 MeV, respectively. For (a) the full histogram is the sum of Reactions (1a) and (1b) while the shaded events are those from (1b) which satisfy the cuts applied to Reactions (2) and (3).

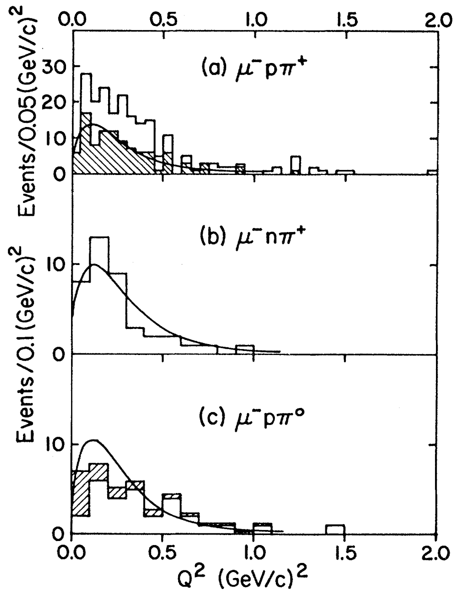

FIG. 2. Distributions of square of four-momentum transfer $Q^2(\nu,\mu^-)$ for events with $M(\pi N) < 1.4$ GeV. For (a) the shaded events are those selected from Reaction (1b). For (c) the shaded events are added to Reaction (3) to make up losses into the quasielastic channel.

which satisfy all the selection criteria for Reactions (2) and (3) which includes the requirement that the spectator momentum be less than 350 MeV/c. The isospin of the final-state hadrons is $\frac{3}{2}$ and the reaction shows nearly pure production of the $\Delta^{++}(1238)$, although the available phase space allows masses above 2 GeV/c^2. Figures 1(b) and 1(c) show the $n\pi^+$ and $p\pi^0$ mass spectra for Reactions (2) and (3), respectively. Although Δ production still occurs, it does not dominate either channel. In particular, there is significantly greater production of high-mass πN systems in these two channels than in the pure $T=\frac{3}{2}$ spectrum of Fig. 1(a).

Figure 2 shows the distributions of the square of four-momentum transfer Q^2. Figure 2(a) shows the sum of Reactions (1a) and (1b) and again the shaded events are those specially selected for comparison from Reaction (1b). The shaded events in Fig. 2(c) are those repopulated as a result of losses into the $\mu^- p p_s$ channel.

Figure 3 shows the excitation function for the three reactions. The cross section for the $\mu^- p\pi^+$ final state [Fig. 3(a)] given for E_ν up to 6 GeV reaches 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.

The final corrected numbers of events for Reactions (1b), (2), and (3) produced by neutrinos below 1.5 GeV are 119.0^{+12}_{-16}, 49.1 ± 10, and 55.5 ± 13, respectively. For πN masses below 1.4 GeV, which is the region of Adler's calculation,[1] the corresponding numbers are 119.0^{+12}_{-16}, 44.0 ± 9, and 43.7 ± 11, respectively.

The amplitudes for the production of various pi-nucleon charge combinations can be written as follows:

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

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

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

where A_1 and A_3 are isovector exchange amplitudes and B_3 is a hypothetical isotensor exchange amplitude[7] with the subscripts denoting twice the isospin of the final hadronic state. If B_3 is zero, the amplitudes $A(\pi^+p)$, $A(\pi^+n)$, and $A(\pi^0p)$ must satisfy a set of triangle inequalities. Moreover,

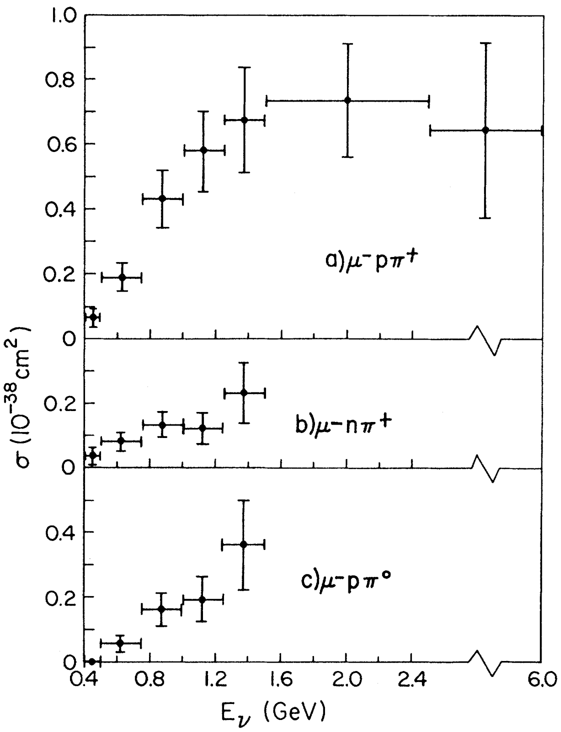

FIG. 3. Excitation function cross sections for Reactions (1)–(3). The errors include a 15% uncertainty in the flux normalization.

if $B_3 \neq 0$, it is still possible with minimal assumptions to set an upper limit on $|B_3/A_3|$.

If $B_3 = A_1 = 0$, then we expect from Eqs. (4)–(6) that

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

and

$$R^{++} = [\sigma(\mu^- n\pi^+) + \sigma(\mu^- p\pi^0)]/\sigma(\mu^- p\pi^+) = \tfrac{1}{3}. \tag{8}$$

Our experimental results [for $M(\pi N) < 1.4$ GeV] $R^+ = 1.01 \pm 0.33$ and $R^{++} = 0.74^{+0.14}_{-0.16}$ imply the existence of at least an A_1 amplitude in addition to the A_3 amplitude. Adler predicts $R^+ = 0.77$ and $R^{++} = 0.58$ for $M(N\pi) \leq 1.4$ GeV, in agreement with these results. The observed πN mass distributions, the Q^2 distributions, and the excitation functions[8] all agree reasonably well with the model, as seen from the curves in Figs. 1 and 2 which represent the detailed predictions of this calculation including the cuts we have applied to our data.

If we assume that isotensor exchange is absent, i.e. $B_3 = 0$, we find that our data satisfy the resulting triangle inequalities. Consequently, $T = 2$ exchange is not required by the data. Assuming that $B_3 = 0$, we have solved for the magnitudes of A_1 and A_3, as well as their relative phase φ for $M(\pi N) < 1.4$ GeV. We obtain $|A_1|/|A_3| = 0.78^{+0.13}_{-0.17}$ and $\varphi = 92^{+10}_{-11}$ deg which is consistent with a resonant $I = \frac{3}{2}$ amplitude in the presence of a large nonresonant $I = \frac{1}{2}$ πN background.

If we allow B_3 to be nonzero but require that it feed only the $\Delta(1238)$ resonance, as does A_3, then it must be real relative to A_3. One then finds the following relationship between the amplitudes:

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

where $\alpha = B_3/A_3$. The resulting triangle inequalities for the magnitudes are satisfied only if $-0.52 \pm 0.11 \leq B_3/A_3 \leq 0.23 \pm 0.07$.

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[1]S. Adler, Ann. Phys. (N.Y.) 50, 189 (1968); see also P. Schreiner and F. Von Hippel, Nucl. Phys. B58, 333 (1973).

[2]J. Campbell *et al.*, Phys. Rev. Lett. 30, 335 (1973). The experimental details described there also apply to the present analysis.

[3]We estimate this correction by using the three-constraint reaction $\nu d \to \mu^- p p_s$, deleting the seen spectator proton, and performing a three-constraint fit with the spectator momentum components constrained to 0 ± 50 MeV/c.

[4]In order to obtain a momentum-transfer–dependent correction function for this loss, we first simulate a sample of Reaction (3) events by taking Reaction (1b) events and treating the π^+ as a π^0. We then find which of these give a quasielastic fit. We find the correction to be independent of πN mass over the Δ mass range.

[5]M. Derrick, 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), p. II-166.

[6]See S. J. Barish *et al.*, Phys. Rev. Lett. 33, 448 (1974), for a discussion of neutron and γ background estimates. In addition, weak neutral currents were estimated to contribute at about this level.

[7]The possibility of an isotensor exchange has been considered by R. J. Oakes and H. Primakoff, Phys.

Rev. D 7, 275 (1973).
[8]See Ref. 2 for a comparison of preliminary data from Reaction (1) with the excitation function calculated in the Adler model. Theoretical curves are not shown in Fig. 3 since the model only describes πN masses below 1.4 GeV.

Search for Stable, Abnormal (Collapsed) Nuclei in Nature*

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Very tightly bound, abnormally-high-density states of nuclei, suggested as a possibility by Bodmer and by Lee and Wick, have been searched for as an anomalous isotope of radon. This was done by looking for high-energy γ rays following thermal-neutron capture. The limit that may be set for the atomic concentration of such nuclides on Earth is $\sim 10^{-29}$ atom of Si.

The possible existence of a very tightly bound, stable, and hitherto unobserved state of nuclear matter was suggested some thirty years ago.[1] More recently Bodmer[2] discussed this possibility in more detail and very recently Lee and Wick[3] suggested a specific model for such a state. This model leads to the expectation of abnormally dense nuclei with large A for which the $N=Z$ isotope would be stable with binding energy of perhaps several hundred MeV per nucleon. Several searches are under way to detect such nuclei in the backscattering of high-energy protons at Fermi National Accelerator Laboratory and to produce them in relativistic heavy-ion collisions at Berkeley.[4] The present experiment was designed to set some limits on the terrestrial concentration of such material.

The most obvious limit one may set for an isotope of small abundance and anomalous mass is from a comparison of the values of atomic masses determined directly by a mass spectrometer and those deduced from stoichiometric chemical measurements. In the case of Bi, for instance, the mass from chemical measurements[5] is 208.976 while the direct measurement[6] is 208.980401. From this one may conclude that the abundance of a Bi isotope with anomalously low mass, $A = 166$ (if $N \approx Z$) and mass $\lesssim 150$, is $\lesssim 6\times 10^{-5}$. One could probably lower this limit by specific searches but not by much more than three or four orders of magnitude.

If there are stable nuclei with binding energies much higher than in normal nuclei, then the capture of an additional neutron should lead to the release of photons with anomalously high energy. If the energy available is greater than ~ 140 MeV, pion emission is likely, and these will likewise lead to high-energy photons, with fair probability.

In order to estimate the capture rate for such a process we first need to estimate the capture cross section at thermal energies. Assume that the level density is sufficiently higher than in normal nuclei so that many resonances occur in the thermal region (the level spacing $D \ll 25$ meV), and assume that the decay width Γ_c of the capturing state (whether it be pure photon decay or pion decay) is larger than the neutron width Γ_n. With these assumptions one gets[7] $\sigma_c \approx 4\pi k^{-1}K^{-1}$ where k and K are the wave numbers of the neutron at infinity and inside the nucleus, respectively. If the potential inside is approximately ten times deeper than in normal nuclei, one gets $\sigma_c \approx 10^{-21}$ cm^2. The analogous situation exists in normal heavy nuclei: By adding a thermal neutron one is above the fission threshold, and $\Gamma_f \gg \Gamma_n$; the fission cross sections are between 0.3 and 3 times 10^{-21} cm^2.

In an experimental search for high-energy γ rays resulting from thermal-neutron capture in the hypothetical tightly bound states, an array of NaI detectors was used to observe γ rays from several samples of material placed 7.3 m away in an 11.4-cm-diam tube passing near the core of the reactor CP-5, where the thermal-neutron flux is about 3×10^{13} neutrons cm^{-2} sec^{-1} (for details see Bollinger and Thomas[8]). The photon