change-degenerate, boson trajectories[11] will have to be re-examined.

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*Alfred P. Sloan Foundation Fellow.

†Present address: CERN, Geneva, Switzerland.

‡Work supported in part by a Ford Foundation Fellowship. Present address: University of San Marcos, Lima, Perú.

§Present address: Physics Department, Purdue University, Lafayette, Ind. 47907.

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¶On leave of absence with the Advanced Technology Application Division of the RANN (Research Applied to National Needs) Program, National Science Foundation, Washington, D. C.

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Study of the Reaction $\nu p \to \mu^- \pi^+ p$†

J. Campbell,* G. Charlton,‡ Y. Cho, M. Derrick, R. Engelmann, J. Fetkovich,§ L. Hyman, K. Jaeger, D. Jankowski, A. Mann,‖ U. Mehtani, B. Musgrave, P. Schreiner, T. Wangler, J. Whitmore,¶ and H. Yuta
Argonne National Laboratory, Argonne, Illinois 60439
(Received 9 October 1972)

We present an analysis of 153 events of the reaction $\nu p \to \mu^- \pi^+ p$ at an average neutrino energy of 1 GeV. The results were obtained using the Argonne 12-ft hydrogen bubble chamber. The reaction is dominated by $\mu^- \Delta^{++}(1236)$ production for which the total cross section rises from threshold to a value of $(0.74 \pm 0.18) \times 10^{-38}$ cm^2 at $E_\nu \gtrsim 1.0$ GeV. The production and decay angular distributions of the Δ^{++} are given. There is no evidence for hadron-lepton mass enhancements.

We present results on the reaction $\nu p \to \mu^- \pi^+ p$ observed in the 12-ft chamber exposed to the neutrino beam at the zero-gradient synchrotron (ZGS). These data, which were obtained from an analysis of 361 000 pictures taken with an H_2 fill of the chamber and 145 000 pictures with a D_2 fill, represent the first experimental study of neutrino interactions in pure hydrogen and deuterium.

The full circulating beam of the ZGS was resonantly extracted with an efficiency of 65% and a spill time of ~20 μsec. On the average, 1.2

$\times 10^{12}$ protons/pulse with a momentum of 12.4 GeV/c were focused into a spot ~5 mm in diameter on a 60-cm-long Be target. A pulsed current of about 250 kA in a magnetic horn focused the π^+'s produced in the target into a 30-m drift space. After the drift space, the hadrons and muons were removed by a 13-m-long iron shield. The bubble chamber,[1] which is a 26-m^3 cylinder of which 16 m^3 is visible to three cameras, is located behind this shield.

The pictures were scanned using a single view at a demagnification of ~7× life size. All the film was rescanned using a different view, and the results of the two scans were compared by a physicist using three views. The overall scanning efficiency for three-prong events was 0.98 ± 0.013. After measurement and passing through the reconstruction and fitting programs TVGP-SQUAW,[2] the events were re-examined by a physicist.

To ensure both adequate track lengths for measurement and good event visibility, we use a fiducial volume of 11.1 m^3 for the cross-section and angular-correlation results, although all the events are displayed in the mass plots. Of the 153 events found, 121 are within the 11.1-m^3 fiducial volume, all of which is seen by a single camera. From the spatial distribution of the events in the fiducial volume, there is no evidence that any are being lost.

Some background reactions which have the same topology as the three-body ν events are (i) $\gamma p \to \pi^+\pi^- p$, (ii) $np \to pp\pi^-$, (iii) other ν-induced reactions, e.g., $\nu p \to \mu^- p \pi^+ \pi^0$, and (iv) charged tracks which scatter, e.g., $\pi^+ p \to \pi^+ p$, $pp \to pp$. We can eliminate (i) by noting that the rate of pair production is much larger than $\pi^+\pi^- p$ production in this energy range, and we see a negligible number of high-energy pairs. By using the measured angles and momenta of the charged tracks, one can show that the background from sources (ii)–(iv) are not important.

We define two quantities: $m^2 = (E_\mu + E_\pi + E_p - m_p)^2 - (\vec{P}_\mu + \vec{P}_\pi + \vec{P}_p)^2$ and φ, the angle of the reconstructed vector momentum of the three charged tracks relative to the beam direction. For neutrino-induced events, both quantities should be zero. Figure 1 shows a scatter plot of the two quantities obtained from 410 candidates in the hydrogen sample. If the positive tracks reconstructed satisfactorily as both π and p, then both results are plotted. One observes a well-defined cluster of events at the expected position of neutrino events. It is clear (using geometry values

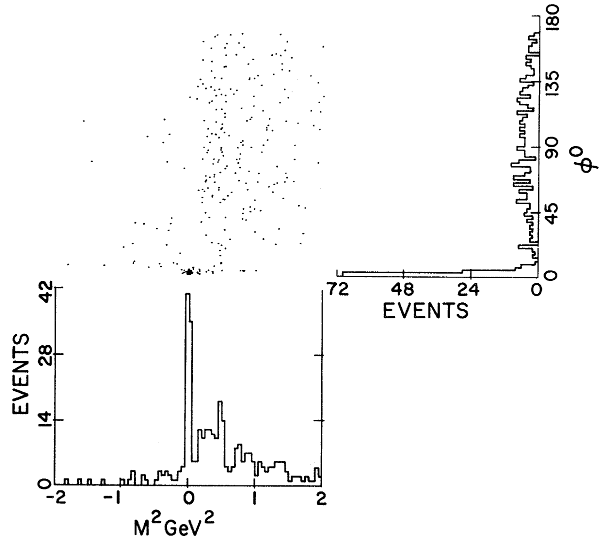

FIG. 1. Scatter plot of the angle φ of the vector momentum of the three charged tracks relative to the ν beam direction versus the mass squared of the beam particle, defined by $m^2 = (E_\mu + E_\pi + E_p - m_p)^2 - (\vec{P}_\mu + \vec{P}_\pi + \vec{P}_p)^2$.

only) that the $\mu^-\pi^+ p$ event selection is clean, and we estimate at most a two-event (2%) background. The fraction of the hydrogen measurements which are classes (ii) and (iii) is ~1% and ~3%, respectively; the great majority of the three-prong measurements belong to class (iv). The scatter plot from the deuterium exposure (308 events) is similar except that the smearing given by the neutron spectator allows a 5% background in this case.

All events were fitted by the $\mu^-\pi^+ p$ hypothesis using program SQUAW. Since the ν beam direction is known to ~1°, the events from the H_2 film can be fitted with three constraints (3C). In D_2 the neutron spectator momentum was given a starting value of 0 ± 50 MeV/c and a 3C fit was also performed. 105 (48) fits were obtained in the H_2 (D_2) sample of film. Fits were also tried with the $\mu^- K^+ p$ and $e^-\pi^+ p$ hypotheses. No event fitted the 3C hypothesis $\mu^- K^+ p$ that also fitted $\mu^-\pi^+ p$. On an individual-event basis, the electron fit could not be ruled out. For the total sample, however, the average χ^2 of the $\mu^-\pi^+ p$ fits was half that of the $e^-\pi^+ p$ fits. Furthermore, all fourteen of the stopping negative tracks decayed into an electron. We also could not discriminate kinematically against the hypothesis $\bar{\nu} p \to \mu^+\pi^- p$, but estimates based on the calculated $\bar{\nu}$ flux indicate that this background is negligible. No identified neutrino event gave an acceptable con-

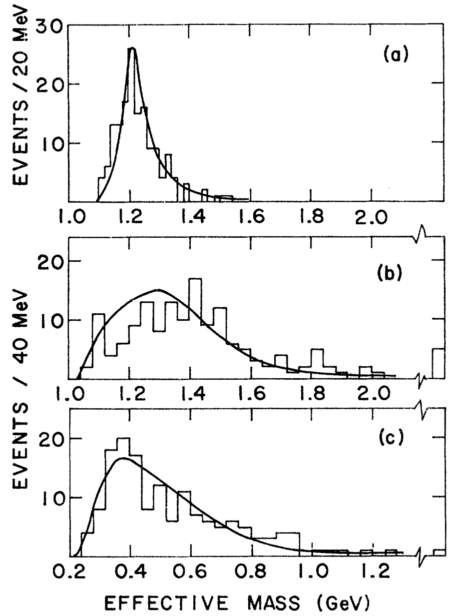

FIG. 2. Three two-body effective mass combinations events of the reaction $\nu p \to \mu^- \pi^+ p$. (a) $\pi^+ p$, the Δ^{++} signal dominates; (b) $\mu^- p$; and (c) $\mu^- \pi^+$. No evidence for enhancements can be seen in the latter two combinations.

strained fit to any other background hypothesis. Our event sample then is consistent with $\nu_\mu p$ interactions only.

In Fig. 2 we show the three two-body effective-mass combinations. It is apparent from the $\pi^+ p$ mass distribution that our data are dominated by $\Delta^{++}(1236)$ production. A fit to the $\pi^+ p$ mass distribution[4] gives the Δ^{++} resonance fraction as 95%. The curves on the $\mu^- p$ and $\mu^- \pi^+$ mass combinations are the expected reflections of the Δ signal in the $\pi^+ p$ effective mass for the observed production and decay angular distributions.

A possible $\mu^- \pi^+$ mass enhancement at 0.42 GeV has been reported[5] in a study of the reaction $\nu + \text{nucleus} \to \mu^- \pi^+ + \text{anything}$. Our results are shown in Fig. 2(c). The $\mu^- \pi^+$ mass resolution is <10 MeV. After plotting the data in various size mass bins and applying various cuts to the data, we conclude that there is no compelling evidence in our experiment for a heavy lepton near 0.42 GeV with narrow width.

In a study of the elastic reaction $\nu n \to \mu^- p$, a possible direct-channel enhancement was reported by Yoshiki[6] at a $\mu^- p$ mass of 1.9 GeV. Our $\mu^- p$ mass spectrum [Fig. 2(b)] shows no enhancement in this region. Figure 3(b) also shows no effect at a ν energy of 1.5 GeV, which would cor-

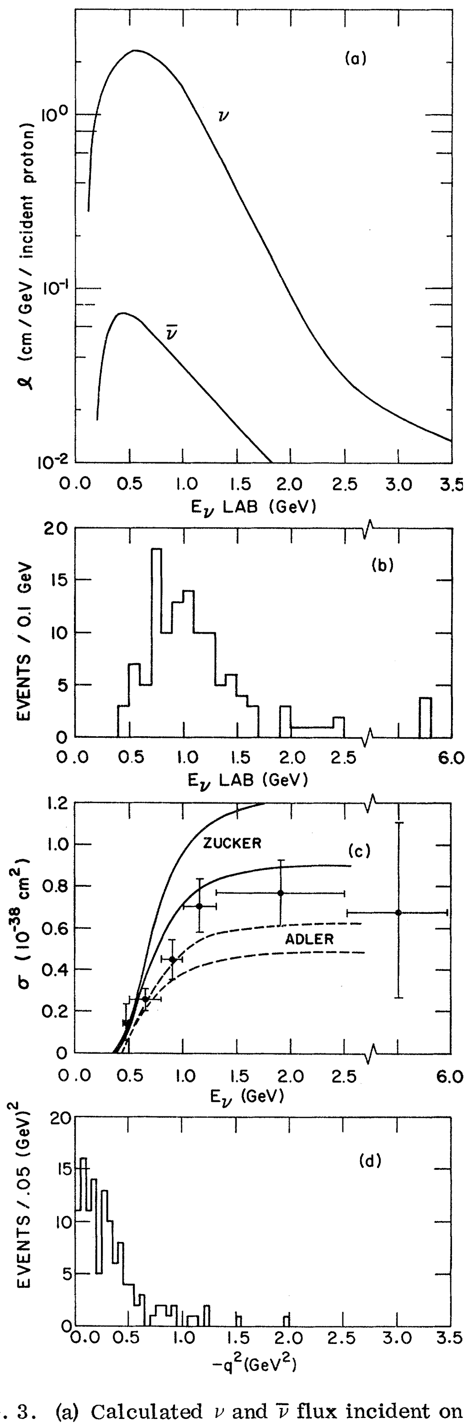

FIG. 3. (a) Calculated ν and $\bar{\nu}$ flux incident on the bubble chamber. (b) Number of events found for different E_ν values. No significant narrow peaks are evident. The four overflow events have $2.5 < E_\nu < 6$ GeV. (c) Total cross section for the reaction $\nu p \to \mu^- \Delta^{++}$ as a function of E_ν. The last point is averaged between $E_\nu = 2.5$ GeV and $E_\nu = 6$ GeV. The errors do not include the flux uncertainty as explained in the text. The theory curves are evaluated with $M_A = 0.74$ and 0.94 GeV. (d) Four-momentum–transfer distribution (q^2) between ν and μ^-.

respond to the $\mu^-\pi^+p$ decay of such an object.

The calculation of the ν flux illuminating the chamber requires a detailed discussion, which we defer to a subsequent publication. Our determination of the flux relies on extensive measurements[7] of the pion production cross section from p-Be collisions at our energy. Two independent computer programs were written to compute the ν flux from the pion production data, and their results agreed well. Many parameters enter such a computation, and at this state, we assign a ± 15% uncertainty to the overall flux normalization, although the uncertainty below 0.5 GeV and above 2.5 GeV is larger. The ν flux we have used is shown in Fig. 3(a) together with the calculated contamination of $\bar{\nu}$'s.

Figure 3(b) shows the number of events as a function of ν energy. The experimental data are predominantly below 1.5 GeV. Figure 3(c) shows our results on the total cross section for the final state $\mu^-\Delta^{++}$ after binning the data into six momentum intervals. The points do not contain the overall normalization uncertainty of ± 15%; they do, however, have a point-to-point relative error in the flux shape of ± 5% folded in, except for the last point which has ± 15% to allow for the uncertainty in the K^+ production cross section which contributes in this region. For $E_\nu \geq 1.0$ GeV, we measure the cross section to be $(0.74 \pm 0.18)\times 10^{-38}$ cm^2 when the error includes the flux uncertainty. This measurement can be compared with the earlier CERN result[8] of $(1.13 \pm 0.28)\times 10^{-38}$ cm^2 for $1 \leq E_\nu \leq 4$ GeV, which was obtained in a propane bubble chamber with about $\frac{1}{3}$ as much data. Although this earlier result is about 50% higher than ours, the two experiments are compatible within the errors.

A number of theoretical calculations have been made of the process $\nu p \to \mu^-\Delta^{++}$.[9] In Fig. 3(c) we show the total-cross-section predictions of two of them[10,11] evaluated with axial-vector form-factor masses M_A of 0.74 and 0.94 GeV. Given the errors on the cross section and on M_A,[12] it is not possible to reject decisively any of the models on the basis of total cross section alone. The four-momentum-transfer distribution shown in Fig. 3(d) for the $\mu^-\Delta^{++}$ final state is also not a good discriminator of the different models.

A more powerful technique, and one which does not depend on the absolute flux normalization, is to compare predicted and measured angular distributions of the Δ decay. Figure 4 displays a scatter plot of the polar (θ) and azimuthal (φ) angles for $\mu^-\pi^+p$ events calculated in the coordinate system used by Adler.[10] The distribution does not exhibit any striking structure nor any evidence for interference effects between the Δ^{++} and nonresonant background. Assuming the absence of background and time-reversal invariance to hold in the Δ production process, the decay distribution can be described by the average values of three spherical harmonics: $Y_2^0 = -0.021 \pm 0.023$, $\mathrm{Re}Y_2^1 = -0.032 \pm 0.020$, and $\mathrm{Re}Y_2^2 = +0.043 \pm 0.019$. These data provide crucial tests of the theoretical models.[9]

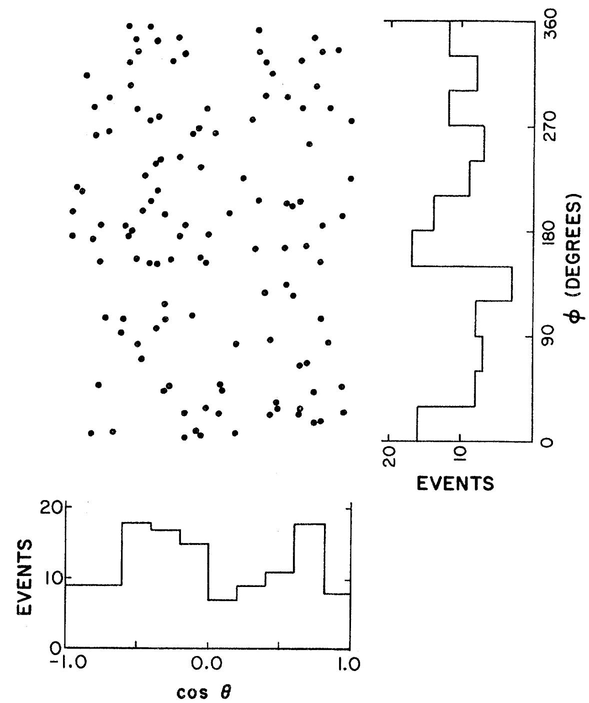

FIG. 4. Distribution of angles of the pion from the Δ^{++} decay. The angles are defined in a right-handed system in which the z axis is along the direction of $\vec{P}_\nu - \vec{P}_\mu$ and the y axis is along the normal to the production plane $(\vec{P}_\nu \times \vec{P}_\mu)$. θ and φ are the usual polar and azimuthal angles.

This experiment was made possible through the dedicated efforts of many people. We owe thanks to E. G. Pewitt and the group that did such a fine job in constructing the bubble chamber. We wish to thank the ZGS staff for the operation of the accelerator and resonant extraction system, W. Praeg for providing reliable operation of the focusing horn, and A. Tamosaitis for the exemplary way in which the bubble chamber ran using both hydrogen and deuterium fills.

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sion.

*Present address: Singer Company, Little Falls, N. J. 07424.

‡Present address: Stanford Linear Accelerator Center, Stanford, Calif. 94305.

§Permanent address: Carnegie-Mellon University, Pittsburgh, Penn. 15213.

||Present address: Tufts University, Medford, Mass. 02155.

¶Present address: National Accelerator Laboratory, Batavia, Ill. 60510.

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[3]There is one example of a negative track which either scatters or decays in flight. We estimate that there is a 10% chance that our sample contains 1 μ^- decay in flight; and hence, we retain this event.

[4]The mass spectrum was fitted using a Breit-Wigner and Lorentz-invariant phase space. The resonance form has been described by J. D. Bjorken and J. D. Walecka, Ann. Phys. (New York) 38, 35 (1966), and R. H. Dalitz and D. G. Sutherland, Phys. Rev. 146, 1180 (1966).

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[10]S. Adler, Ann. Phys. (New York) 50, 189 (1968).

[11]P. Zucker, Phys. Rev. D 4, 3350 (1971).

[12]The world average value for M_A from published data is ~0.84 GeV, although a recent preliminary result from Argonne [as reported at the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published)] indicates a somewhat higher value.

$\nu p \to \mu^-\Delta^{++}$: Comparison with Theory*

Philip A. Schreiner and Frank von Hippel
Argonne National Laboratory, Argonne, Illinois 60439
(Received 9 October 1972)

New data on the reaction $\nu p \to \mu^-\Delta^{++}$ are compared with theoretical predictions. We stress the importance of the Δ spin-density matrix in making decisive tests of the models. The data are consistent with the prediction using partially conserved axial-vector currents for $d\sigma/dq^2$ near $q^2=0$. In contrast to previous findings, Adler's relativistic version of the static model is reasonably successful in fitting the data. Zucker's model also fits the data.

During the past decade many theoretical calculations of $\Delta(1236)$ production by neutrinos have been published. Some of these predictions depend upon the validity of the hypotheses of conserved vector currents (CVC) and partially conserved axial-vector currents (PCAC), while others rely on model-dependent assumptions concerning the dominance of particular Born diagrams. Thus far, only the predictions for the Δ production cross section have been compared with data, consisting of a single low-statistics experiment in the CERN propane bubble chamber.[1] This comparison resulted in the apparent failure of the relativistic extension of the static model which had previously successfully accounted for the major features of Δ photoproduction and electroproduction for $|q^2|<0.5$ GeV^2.[2]

In this Letter we show that this model, which incorporates PCAC, successfully predicts both the cross sections and Δ density-matrix elements measured in the recent Argonne hydrogen bubble-chamber experiment[3] and that, in contrast, some other models which had successfully fitted the CERN cross-section results are in disagreement with the Argonne density-matrix elements. The experimental statistics are not yet adequate, however, to provide a stringent test of this model or, in fact, to favor it over all others (e.g., Zucker's model).[4] Our analysis will appear in greater detail elsewhere.

Following Berman and Veltman[5] and using the notation of Llewellyn-Smith,[6] the invariant matrix element for the reaction $\nu(q_1)+p(P_p)\to\mu^-(q^2)+\Delta^{++}(P_\Delta)$ may be written in terms of Rarita-Schwinger form