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# SOME PROPERTIES OF THE HADRONIC SYSTEM IN NEUTRINO INTERACTIONS

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## INTRODUCTION

This paper does not attempt to review all that has been learned about hadrons in neutrino interactions. Rather, it presents a few selected topics that are all results from bubble-chamber experiments with high-energy neutrinos, primarily those experiments using the Fermilab 15-ft bubble chamber shown in Fig. 1.

Many experiments have examined the gross features of the hadronic system in $\nu$ in $\overline{\nu}$ interactions in both hydrogen and heavy liquids, particularly charged particle multiplicities and transverse momentum distributions. These studies tried to determine if hadrons from neutrino interactions (hadrons that are presumably produced by collisions of intermediate bosons with hadronic matter) look like hadrons produced by hadrons or by photons. So far such experiments have concluded that hadronic systems look the same regardless of their origin.

## INCLUSIVE DISTRIBUTIONS

It is fashionable to analyze inclusive hadron distributions in terms of the Quark Parton Model (QPM). In this model, the dominant process for neutrino interactions is the conversion of a down quark into an up quark: $\nu d \rightarrow \mu^- u$. Inclusive distributions can be interpreted in terms of the quark fragmentation functions $D_q^h(z)$ that describe the fragmentation of quark q into hadron h as a function of z, the fraction of the hadronic momentum carried by the hadron.

Examples of this type of z distribution analysis are taken from John Marriner,[1] who used data from Berkeley-CERN-Hawaii-Wisconsin (BCHW) collaboration. The BCHW experiment used 300-GeV protons and a 1-horn beam to send neutrinos into a neon-hydrogen mix in which 21% of the atoms were neon. The results came from a sample of more than 1000 charged-current events. The signal for events with muons above 3 GeV was entirely determined by using the External Muon Identifier (EMI). Figure 2 shows the energy distribution of the charged-current events in this sample.

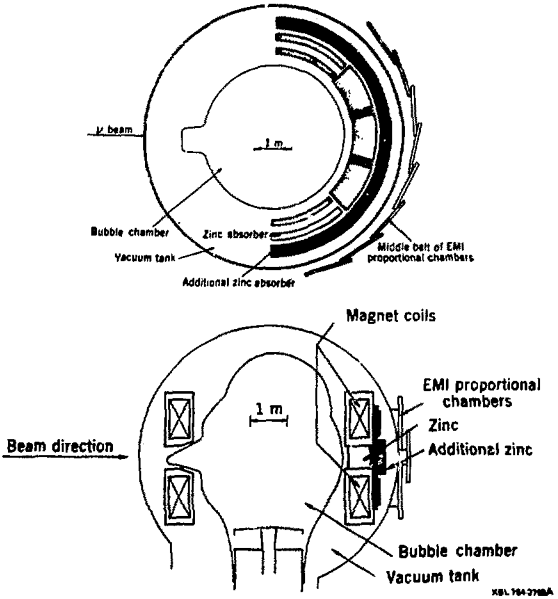

Fig. 1. The 15-ft Fermilab bubble chamber.

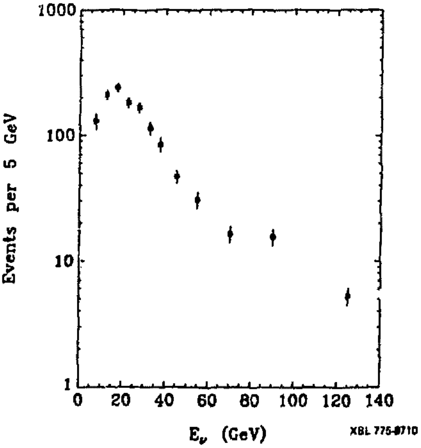

Fig. 2. The energy distribution of charged-current events from 300-GeV protons and 1-horn beam (from reference 1).

The z distribution for positive and negative hadrons in this charged-current sample is shown in Fig. 3. The curves are the predictions of the QPM as parameterized by Field and Feynman[2] and normalized to the data for $z > 0.2$. One cannot expect this model to fit the data at small z at finite neutrino energies. Above $z = 0.2$ the curves fit the data remarkably well, accurately predicting the large excess of positives over negatives at large z.[3]

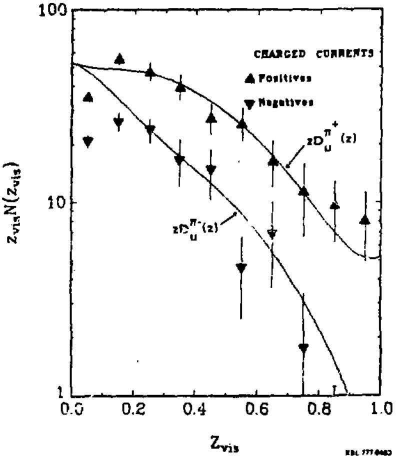

Fig. 3. The distribution for positive and negative tracks in charged-current events. The curves are predictions of Field and Feynman[2] for pions, normalized to the data for $z > 0.2$ (from reference 1).

Although this agreement demonstrates that the QPM is able to fit the data, it is not a discriminating test of the QPM. At LBL, we have a Monte Carlo program that knows nothing about quarks. All it knows about hadrons is momentum, energy and charge conservation, and that hadron systems have limited transverse momentum. The Monte Carlo program also fits the z distribution. The excess at large z for $\pi^+$ at finite energies is primarily a consequence of charge conservation. This illustrates that to test QPM, one must find tests in which the predictions of QPM differ from the consequences of phase space with limited transverse momentum.

Because the QPM fits well with the charged-current z distribution for $z > 0.2$, the model can be used to learn about the hadron system in neutral-current events. In the BCHW experiment, a sample of neutral-current events was studied.[1] Care was taken to correct for contamination by charged-current events and events produced by neutral hadrons. The charged-current contamination was reduced to a manageable level by including in the neutral-current sample only events in which the negative track with the largest transverse momentum interacted in the bubble chamber. The hadron contamination was brought to a manageable level by using only events with a visible momentum greater than 10 GeV. The hadron contamination was corrected for by making use of the fact that hadron interactions are usually associated with another interaction in the bubble chamber. This neutral-current analysis yields

$$R = \frac{\sigma_{NC}}{\sigma_{CC}} = 0.35 \pm 0.06$$

for hadronic energies greater than 10 GeV.

Figure 4 shows the z distributions for positives and negatives for this neutral-current sample. The curves are the best fit to the data using the quark fragmentation functions of Field and Feynman along with one fitted parameter that describes the relative contributions of the u and d quarks to the neutral-current cross sections. The best fit is that the d quark is responsible for 56 ± 10% of the cross section. For comparison, the prediction of Field and Feynman is 58 ± 10% of the cross section. Thus the fitted value is in good agreement with the expectation, even though the fitted curve is only in fair agreement with the data.

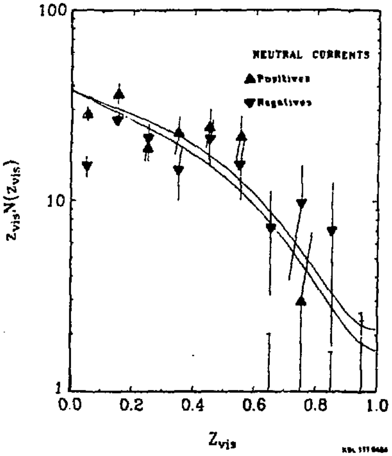

Fig. 4. The z distribution for positive and negative tracks in neutral-current events. The curves are the predictions of Field and Feynman[2] normalized to the data for $z > 0.2$ (from reference 1).

## DILEPTION EVENTS

Although the gross features of the hadron system seem to be universal, hadron systems from neutrino interactions almost certainly have more charmed particles than hadron-produced hadron systems. For neutrino interactions, the most important quark reaction is the Cabbibo suppressed reaction

$$\nu d \rightarrow \mu^- c \quad . \text{(Ref. 4)}$$

The evidence for charmed-particle production in neutrino reactions comes from observation of dilepton events, which are events containing two charged leptons. Counter-experiments first saw dilepton (dimuon) events, measured the rates of their occurence, and demonstrated that dimuon events are compatible with charm-particle models.[5] A number of bubble-chamber experiments have observed dileptons from neutrinos, mostly $\mu e$ events.[6] All of these experiments are consistent with a dilepton production rate ($\mu\mu$ or $\mu e$) of 0.5% of all charged-current events.

In no case has an individual charmed particle been identified in these bubble-chamber experiments. It is not known if these events are due to the production of D mesons or some other charmed particles. The only additional evidence that charm is being produced in these experiments is that the dilepton events have an anomalously large number of strange particles, as expected from the decay of charmed particles.

Table I summarizes the strange-particle content of the dilepton events reported thus far. The experiments are in poor agreement concerning the number of visible $V^o$s per event. If in spite of this, we average all of the experiments, the result is 0.38 ± 0.07 (statistical error only) visible $V^o$ per dilepton event, far greater than the 0.08 observed in all charged-current events. If we assume that 0.38 is correct, we can calculate how many $V^o$s each of these experiments should have seen. This prediction is shown in Table I along with the probability of getting a disagreement as large as the one observed. (For example, for BCHW the 1.1% disagreement probability is twice the binomial probability of getting 11 or more $V^o$s out of 17 dileptons when the average number of $V^o$s is 5.4.)

If the true proportion of $V^o$s per event is 0.38, then the probability of getting three experiments that disagree as much as the BCHW, CB, and BEBC experiments is about 0.3%. So there is little chance that this disagreement is statistical. However, if BCHW and CB both have systematic errors on the order of 20%, the statistical disagreement is not very bad. For example if we give two of the Vs from BCHW to CB (less than a 20% change in each case), then the disagreement is about 5%. On the other hand, to make these experiments compatible with no extra $V^o$ production would require an average systematic error of more than a factor of 2.

Table I. Tabulation of the $V^0$ content of observed dilepton events in five experiments.[6]

| Experiment | BCHW | CB | BHS | BHF | BEBC | Total |
|---|---|---|---|---|---|---|
| Number of dileptons | $17e^+$ | $81e^+$ | $6e^+$ | $9\mu^+$ | $10\mu^+$<br>$+5e^+$ | 128 |
| Estimated background | 0.5 | 12 | 0.6 | 2.4 | 2.3 | 18 |
| Number of $V^o$s | 11 | 15 | 1 | 1 | 7 | 35(a) |
| Average number of $V^o$s per event(b) | 0.78 | 0.25 | 0.22 | 0.15 | 0.67 | 0.38±0.07 |
| Predicted number of $V^o$s(b) | 5.4 | 22 | 1.7 | 2.3 | 4.0 | -- |
| Probability of a disagreement this large | 1.1% | 8.7% | -- | -- | 16% | -- |

(a) The 35 $V^o$s are composed of 25 $K^o$s, 3 $\Lambda_s$ and 7 ambiguous Vs.

(b) In calculating the number of $V^o$s per event and the predicted number of $V^o$s, it was assumed that background events have 0.08 $V^o$ per event. The detection probability was taken to be 85% for BCHW and 80% for the others. (The 5% difference takes into account the difference in the interaction probability in the different liquids.)

Therefore, even though there are probably serious systematic errors in some of these experimen..., one can still conclude that the dilepton events have considerably more strange particles than ordinary charged-current events. The 25 to 32 $K^o$s lead to an estimate of 0.8 to 1.0 $K^o$ per event (±0.2).

## EXCLUSIVE CHANNELS

### Charmed Hyperon Searches

What we would like to find in these bubble-chamber neutrino experiments is not merely the taste of charm given by the excess of strange particles, but identification of individual charmed particles, preferably in well-constrained, well-understood events. One familiar candidate for such an event (often referred to as the Samios event) was reported in 1975 in a Brookhaven experiment.[7] There, an event was found that fit the reaction $\nu p \rightarrow \mu^- \Lambda \pi^+ \pi^+ \pi^+ \pi^-$, with $E_\nu = 13.5$ GeV and the hadron mass $W = 2426$ MeV. Such an event with $\Delta S = -\Delta Q$ cannot be explained by conventional pre-charm theories and could be the production of a charmed baryon.

The Berkeley-Fermilab-Hawaii-Michigan (BFHM) experiment[8] in hydrogen was done in the 15-ft Fermilab chamber. This experiment now has about 200 times the flux at 13.5 GeV that the Brookhaven experiment had when this event was reported, and more than 10 times the flux above 4 GeV (approximate charm threshold). The BFHM experiment has only one good event that fits $\nu p \rightarrow \mu^- \Lambda \pi^+ \pi^+ \pi^+ \pi^-$ and none that fit $\nu p \rightarrow \mu^- \Lambda \pi^+ \pi^+$. However this event has a $\pi^+ \pi^-$ combination that has the mass of the $K^0$ with an error of 4 MeV. The event may be $\nu p \rightarrow \mu^- \Lambda \pi^+ \pi^+ K^0$ with the $K^0$ very short. Thus the BFHM experiment has no convincing candidate for the production of a charmed baryon, and the cross section for this process is much smaller than was suggested by the Brookhaven event.

## The Reaction $\nu p \rightarrow \mu^- p \pi^+$

From this point on, all of the data presented are from the BFHM neutrino experiment in hydrogen.[8] The results are from a sample of about 3000 charged-current events. In this experiment, a clean sample of the reaction $\nu p \rightarrow \mu^- p \pi^+$ was obtained and studied. To do this we started with the sample of three prong events above 5 GeV that are not closer than 50 cm from the back wall of the chamber. We further restricted the sample to those events in which the negative track does not interact and the choice of $p\pi^+$ is not excluded for the positive tracks. If we assume the reaction has the form $\nu p \rightarrow \mu^- p M^+$, where the mass of the $M^+$ is not fixed we can calculate the mass of the $M^+$. Figure 5 shows the mass distribution resulting from such calculations. Even without using the known beam direction, the $\mu^- p \pi^+$ events stand out and the meson mass resolution is quite good (typically 10 MeV).

However, we know the beam direction of the neutrinos to better than 1 milliradian. When we use this known beam direction, by requiring the missing transverse momentum to be consistent with zero, we get the histogram in Fig. 6 (the result of kinematic fits having two constraints). In Fig. 6 the pion peak is quite clean, but because of the background we cannot tell if there is a peak at the K mass. Most of this background is due to events that have tracks with poorly measured momenta (usually because the tracks are short). We can eliminate the background by requiring well-measured events. A clean sample of three-body events was then obtained by requiring $E\delta\phi\delta\lambda < 0.1$ MeV steradian and $\delta M < 50$ MeV, where $\delta\phi$ and $\delta\lambda$ are the uncertainty in the measured direction of the vector sum of the momenta of all three particles, and $\delta M$ is the uncertainty on the

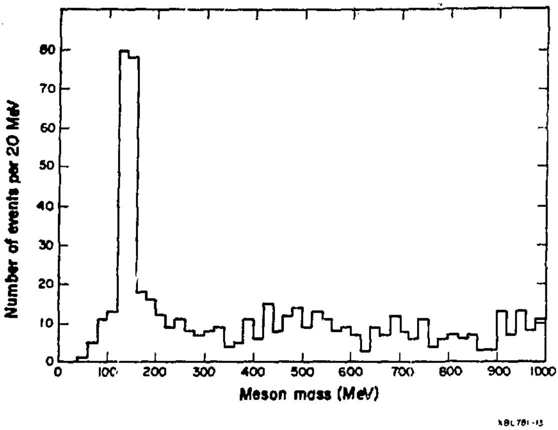

Fig. 5. Distribution in meson mass for the assumed reaction $\nu p \rightarrow \mu^- p M^+$ for all three-prong events above 5 GeV in the fiducial volume for which track identification does not exclude the $\mu^- p \pi^+$ combination (563 events in plot; 316 events overflow).

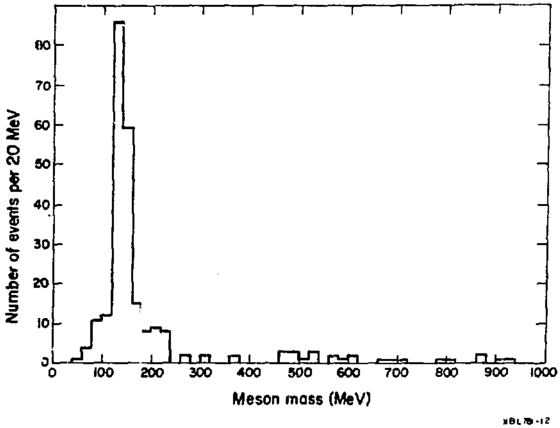

Fig. 6. Distribution in meson mass for the assumed reaction $\nu p \rightarrow \mu^- p M^+$ for events plotted in Fig. 5 that are consistent with no missing transverse momentum (243 events in plot; 12 events overflow).

mass of the $M^+$. The mass distribution for this sample is shown on Fig. 7. Here, about 80% of the events in the pion peak survive this cut and almost all of the background is eliminated.

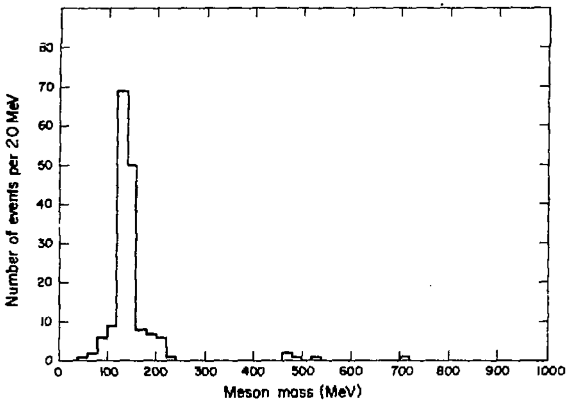

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Fig. 7. Distribution in meson mass for the assumed reaction $\nu p \rightarrow \mu^- p M^+$ for those events in Fig. 6 that have small errors (164 events in plot). See text for explanation of well-measured events.

There is a small but clear signal of three events at the kaon mass in Fig. 7 showing that the ratio

$$\frac{\sigma(\nu p \rightarrow \mu^- p K^+)}{\sigma(\nu p \rightarrow \mu^- p \pi^+)} = \frac{3}{160}$$

in this energy range.[9] The one event at 522 MeV in Fig. 7 is not a kaon event. Not only is the $M^+$ mass more than four standard deviations from a kaon mass but one track is identified as a pion.

There is one oversimplification in this presentation. For some events there is an ambiguity about which track is the proton and which is the meson. Only about 10% of the events in the pion peak have this ambiguity. In every one of the meson mass plots (Figs. 5, 6, and 7), we chose the solution closest to the pion mass when such an ambiguity existed. All three of the kaon events are ambiguous and in each case the high mass solution is between 700 and 800 MeV.

This analysis shows that we can get a clean sample of $\mu^- p \pi^+$ events separated from other neutrino interactions with missing neutrals. One background that is not separated in this way is the background from $K_L^0 p \rightarrow K^- p\pi^+$. Events that fit $\nu p \rightarrow \mu^- p\pi^+$ almost always fit this $K_L^0$ reaction. We can determine the background from this reaction, combined with the background from neutrino interactions, by looking at the histogram of the quantity $E_\nu \sin^2\theta_\nu$, where $\theta_\nu$ is the angle between the sum of the momenta of the visible tracks and the beam direction. If we select well-measured events (with $E_\nu \delta\phi\delta\lambda < 0.1$ MeV steradian) then the $\nu p\pi^+$ events should have $E_\nu \sin^2\theta_\nu \lesssim 0.1$ MeV steradian, whereas background events from $K_L^0$ or neutrino should have a distribution in $E_\nu \sin^2\theta_\nu$ that is rather flat out to 10 MeV steradian. Figure 8 shows such a plot for those events that fit $\nu p \rightarrow \mu^- p\pi^+$ (with the beam direction unconstrained). Clearly, the background from false events in the pion peak is on the order of one or two events.

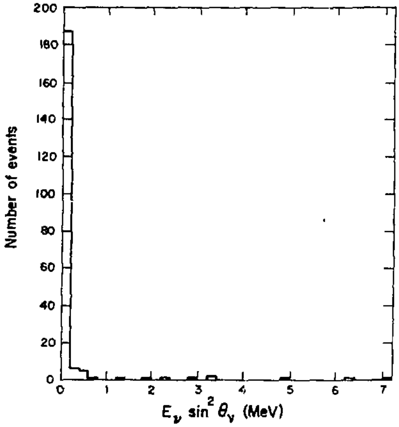

Fig. 8. Distribution in the variable $E_\nu \sin^2\theta_\nu$, where $\theta_\nu$ is the angle between the sum of the visible momenta and the beam direction, for events that fit $\nu p \rightarrow \mu^- p\pi^+$, excluding those with large angle errors.

Using the most accurately measured of these events, we calculate that the neutrino beam direction is $\phi = -2.491 \pm 0.006$ and $\lambda = -0.005 \pm 0.006$ degrees with an rms spread of about 0.04 degrees. Because the actual spread in the beam is close to 0.02 degrees, this spread of 0.04 degrees is mostly a measure of systematic errors. The data from all four (BFHM) laboratories are in agreement with these values of $\phi$ and $\lambda$, which are remarkably close to the nominal values of -2.5 and 0 degrees. From the divergence of the beam in the chamber, we calculate that the target is 1.2 ± 0.2 km away from the bubble chamber. The correct answer in this case is tarnished by the poor agreement among the data from the different laboratories.

Figure 9 shows the $p\pi^+$ mass spectrum from the $\nu p\pi^+$ events. The peak of the $\Delta^{++}$ is clear. In analyzing the reaction $\nu p \rightarrow \mu^-\Delta^{++}$, we used all 147 events with $M_{p\pi^+}$ less than 1400 MeV.[10]

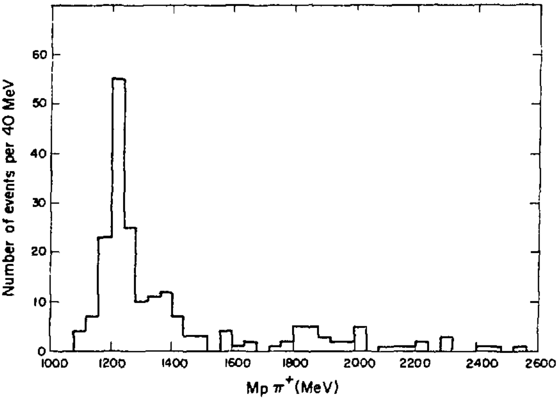

Fig. 9. The distribution of the proton $\pi^+$ mass for $\nu p \rightarrow \mu^- p\pi^+$ events (203 events in plot; 17 events overflow).

Figure 10 shows the distribution of the neutrino energy for these $\Delta^{++}$ events. To the extent that the $\mu^-\Delta^{++}$ cross section is a constant, which should be a good approximation, this plot is a measure of the neutrino flux distribution for the BFHM experiment.

Figure 11 shows the $Q^2$ distribution for the $\mu^-\Delta^{++}$ events. This distribution is interesting because it gives us information about the axial vector coupling constant for the nucleon vertex. The $Q^2$ distribution depends upon both the vector and the axial vector form factors. The vector form factor can be determined from electroproduction experiments. The curves on Fig. 11 show the prediction of Adler's model[11] using a dipole form factor of $(1 + Q^2/M_A^2)^{-2}$. Previous experiments at lower energies have been consistent with a value of $M_A = 0.91$ GeV.[12] The data in Fig. 11 are not consistent with this value but are consistent with $M_A = 1.5$ GeV. This indicates that the parametrization used is not adequate to describe $\Delta^{++}$ production at all energies.[13]

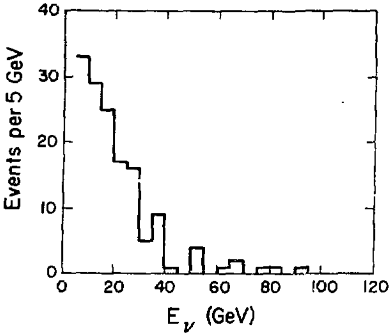

Fig. 10. The distribution of neutrino energies for the reaction $\nu p \rightarrow \mu^- \Delta^{++}$. Median energy above 5 GeV is 17 GeV.

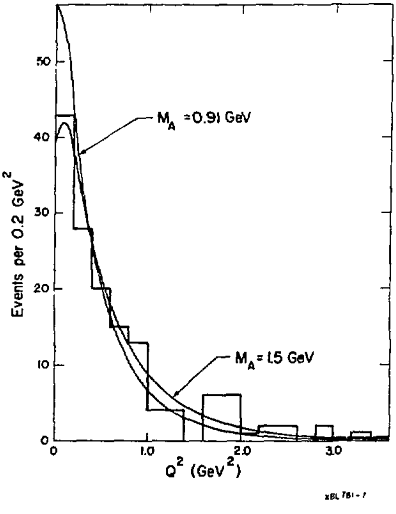

Fig. 11. The distribution of $Q^2$ for $\nu p \rightarrow \mu^- \Delta^{++}$ events. The curves are predictions of Adler's model[11] normalized to the data for two values of the mass $M_A$ that characterizes the axial vector form factor.

## Five-Prong Exclusive Channels

The BHFM experiment looked for evidence of charmed particles in the exclusive channels in the five-prong events and used a cleanup procedure similar to the one used in the three-prong events. The procedure eliminated an estimated 30% of the true exclusive events. The unambiguous fits obtained were:

| | |
|---|---|
| $\nu p \to \mu^- p \pi^+ \pi^+ \pi^-$ | 80 events, |
| $\nu p \to \mu^- p \pi^+ K^+ K^-$ | 8 events, |
| $\nu p \to \mu^- p \pi^+ K^+ \pi^-$ | 3 events, |
| $\nu p \to \mu^- p \pi^+ \pi^+ K^-$ | 1 event, and |
| $\nu p \to \mu^- p K^+ K^+ K^-$ | 1 event. |

The estimated background in each channel was about one event. So there was no signal above background in the $\pi^+\pi^+K^-$ and $K^+K^+K^-$ channels.

The $\pi^+\pi^+K^-$ event is interesting because it might contain a D or a $D^*$. But this one event is not a D nor a $D^*$. Of the eight events of $\mu^- p \pi^+ K^+ K^-$, four have a $\pi^+K^+K^-$ mass below 1800 MeV, and three have a mass greater than 2300 MeV. The one remaining event has a $\pi^+K^+K^-$ mass of 2038 ± 4 MeV. Because the lead glass wall experiment at SPEAR has reported evidence for an F meson with a mass of 2040 that decays into $\pi^+K^+K^-$,[14] this event is a good candidate for the process $\nu p \to \mu^- p F^+$.

## FOOTNOTES AND REFERENCES

1. J. Marriner, Hadronic Structure of the Weak Neutral Current, Lawrence Berkeley Laboratory, Berkeley, Rept. LBL-6438 (1977).

2. R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590 (1977).

3. This comparison is inexact because the prediction is for pions whereas the data include all charged particles except slow protons.

4. For $\bar{\nu}$ charm production, the dominant reaction should be $\overline{\nu s} \to \mu^+\bar{c}$, an interaction with the strange sea. The analogous reaction $\nu s \to \mu^- c$ is a also important in $\nu$ interactions. If the fraction of events with charm is the same for $\nu$ and $\bar{\nu}$ interactions, and the $\bar{\nu}$ cross section is 40% of the $\nu$ cross section, then the simple quark picture says that charm production in $\nu$ interactions is 60% from $\nu d \to \mu^- c$ and 40% from $\nu s \to \mu^- c$.

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   BHF (Berkeley-Hawaii-Fermilab). The results quoted here are preliminary results from this experiment.

   BEBC (Big European Bubble Chamber). P. O. Hulth, private communication, Aug. 1977.

7. E. Z. Cazzoli et al., Phys. Rev. Lett. 34, 1125 (1975).

8. See J. W. Chapman et al., Phys. Rev. D14, 5 (1976) and F. A. Harris et al., Phys. Rev. Lett. 39, 437 (1977) for a description of this experiment.

9. An event of $\nu p \to \mu^- p K^+$ has been reported before in S. J. Barish et al., Phys. Rev. Lett. 33, 1466 (1974).

10. An analysis of about one-fourth of this sample is contained in H. T. French, Single Pion Production by High Energy Neutrinos in a Hydrogen Bubble Chamber, Ph. D. Thesis, University of Michigan (1977).

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13. Another experiment that finds this parametrization inadequate (in their case for elastic scattering) is described in S. J. Barish et al., Study of Neutrino Interactions in Hydrogen and Deuterium, Argonne National Laboratory, Rept. ANL-HEP-PR-76-69 (1977).

14. The evidence for the F meson at SPEAR is presented at this conference by D. Lüke.

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