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Cross-section ratio $\sigma(\nu n)/\sigma(\nu p)$ for charged-current and neutral-current interactions below 10 GeV

P. F. Jacques, M. Kalelkar, P. A. Miller,* R. J. Plano, and P. Stamer[†]
Rutgers University, New Brunswick, New Jersey 08903

E. B. Brucker, E. L. Koller, and S. Taylor
Stevens Institute of Technology, Hoboken, New Jersey 07030

C. Baltay, H. French, M. Hibbs, R. Hylton, K. Shastri, and A. Vogel[‡]
Columbia University, New York, New York 10027
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We have measured the cross-section ratio $\sigma(\nu n)/\sigma(\nu p)$ for both charged-current and neutral-current interactions at low energy. The experiment used the wide-band neutrino beam at Brookhaven National Laboratory. The detector was the 7-foot bubble chamber filled with a 62% neon–hydrogen mixture. For charged-current events we find that the ratio reaches an asymptotic value of 1.80 ± 0.19 for neutrino energies above 1 GeV. For neutral-current events we measure the ratio to be 1.07 ± 0.24. Both of these results are in agreement with the quark model.

We have performed a measurement of the cross-section ratio for the reactions

$$\nu_\mu + n \to \mu^- + \text{hadrons}, \qquad (1)$$

$$\nu_\mu + p \to \mu^- + \text{hadrons} \qquad (2)$$

with incident neutrino energies below 10 GeV. Since charged-current (CC) neutrino scattering occurs only off d quarks, the naive quark model predicts a value of 2.0 for the cross-section ratio $R_{CC}=\sigma(\nu n)/\sigma(\nu p)$ counting only the valence quarks. The presence of sea quarks is expected to modify this value, and there have been several attempts[1-3] to calculate the corrected value of R_{CC}. Theoretical predictions range from 1.54 to 2.50. Field and Feynman[4] have used fits to electroproduction data to derive quark structure functions, which then predict a value of 1.95 for the ratio. There have been two measurements of R_{CC} at low energies, one[5] yielding the value 1.95 ± 0.21, and the other[6] 2.08 ± 0.15. At energies above 10 GeV, the value 2.03 ± 0.28 has been reported.[7] The corresponding ratio for antineutrino scattering has been measured in two experiments.[8,9]

We also report a measurement of the cross-section ratio for the neutral-current (NC) reactions

$$\nu_\mu + n \to \nu_\mu + \text{hadrons}, \qquad (3)$$

$$\nu_\mu + p \to \nu_\mu + \text{hadrons}. \qquad (4)$$

The ratio R_{NC} for these reactions is expected to be 1.0. There are no published measurements of R_{NC}. The only reported value[10] is 1.02 ± 0.19.

Our experiment was performed at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) using the horn-focused wide-band neutrino beam. The 28-GeV/c proton beam from the AGS was incident on a copper target. Positively charged mesons from the target were horn-focused and allowed to decay in a 60-m tunnel. The decay muons were suppressed in a 30-m iron shield. Neutrino interactions were detected in the 7-foot bubble chamber, located 13 m downstream of the shield, filled with a 62% (atomic) neon–hydrogen mixture. The chamber liquid had a density of 0.75 g/cm^3, and a fiducial mass of 2.8 tons.

A total of 212 000 pictures was taken and scanned. All interactions were measured, along with vees and electron-positron pairs coming directly from an interaction vertex. Since the chamber liquid had a radiation length of 40 cm, electrons were readily identifiable by bremsstrahlung and characteristic spiral. The measurements were pro-

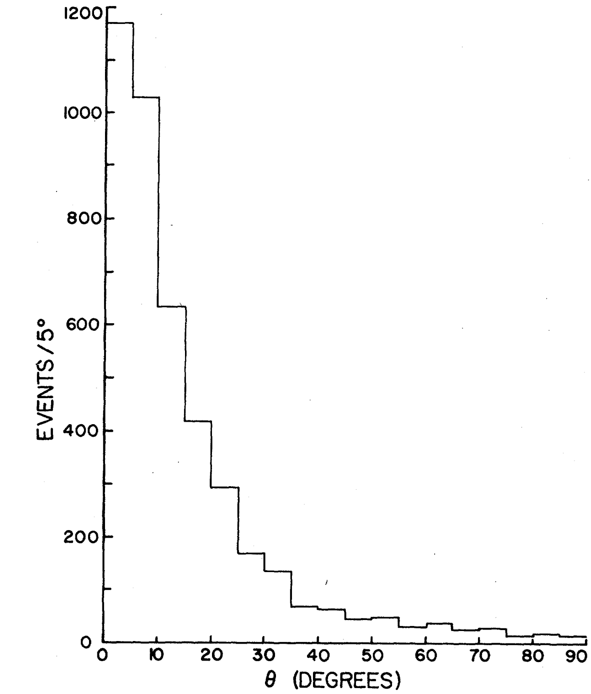

FIG. 1. Distribution of the angle between the total visible momentum and the neutrino-beam direction for charged-current candidates. The visible momentum includes the muon, the charged hadrons, and those neutrals decaying or converting visibly in the bubble chamber.

cessed through our version of the geometry program TVGP.

To select candidates for the charged-current reactions (1) and (2), we looked for events with at least one negative leaving track. Since the liquid had an interaction length of 125 cm, muons usually left through the chamber wall, while hadrons typically interacted within the liquid. The fastest negative leaving track in any event was

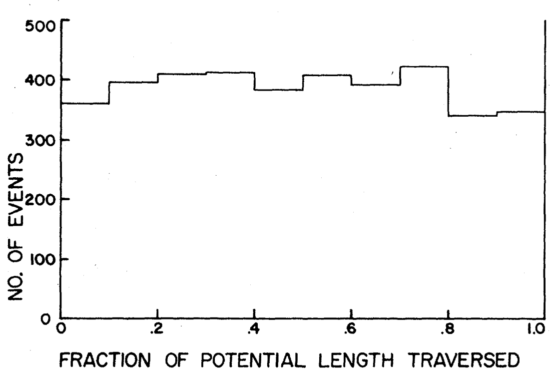

FIG. 2. Fraction of the potential path length (in the bubble chamber) traversed by the neutrino, for the charged-current sample. This distribution is expected to be flat for true neutrino-induced events.

taken to be a μ^-. Also included among the charged-current candidates were a few events with decaying or stopping muons identified from range-momentum correlation. A total of 4511 candidates was obtained.

Figure 1 shows the distribution of the angle between the total visible momentum and the neutrino beam direction. We defined our charged-current sample by requiring this angle to be less than 45°, so as to eliminate the cosmic-ray background. We then get 3979 events surviving this cut. Figure 2 shows, for these events, the fraction of the potential path length in the chamber traversed by the neutrino. This distribution is flat, as expected for neutrinos, whereas neutron-induced events would exhibit attenuation.

The largest background in our sample consists of neutral-current events with a negative hadron leaving the chamber without interacting, thereby faking a μ^-. To calculate this "punchthrough" background, we note that the positive tracks in neutrino interactions are hadrons, so that the ratio of positive leaving to positive interacting tracks is a measure of the punchthrough probability. By using this ratio and counting the numbers of interacting and leaving negative tracks in all the measured events, we determined the punchthrough background to be $(8.6 \pm 1.6)\%$.

To determine the neutrino energy for each event, corrections are necessary to the total visible measured energy. Secondary interactions in the neon nucleus can give rise to "evaporation" protons from nuclear breakup. We removed all stopping protons with momentum less than 0.3 GeV/c (kinetic energy of 50 MeV). We also corrected for undetected neutrals. The component of the missing momentum perpendicular to the

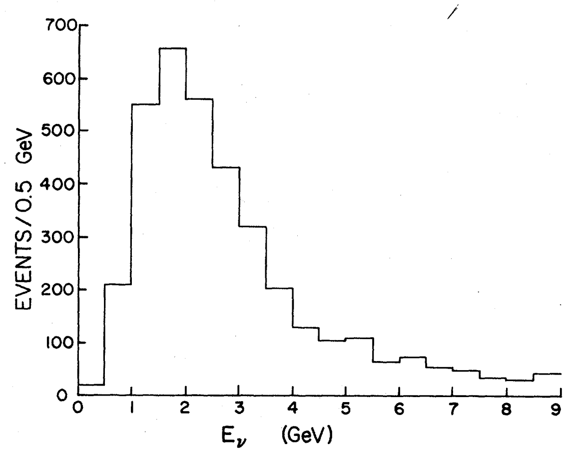

FIG. 3. The corrected neutrino energy distribution for charged-current events. The measured energy in each event was corrected for undetected neutrals by using a method based on transverse-momentum balance.

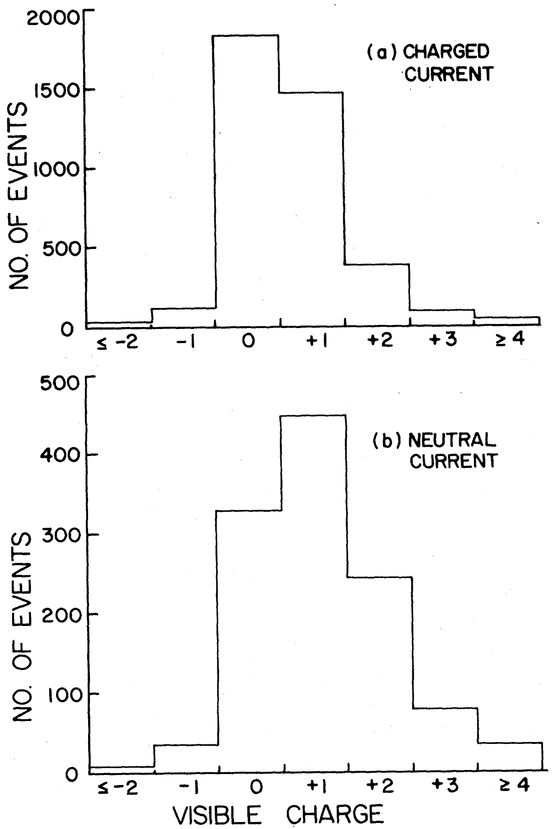

FIG. 4. Visible-charge distribution for (a) charged- and (b) neutral-current events. In the absence of nuclear re-interactions, all events would have a visible charge of 0 or +1.

ν-μ plane was chosen to balance the corresponding component of the visible momentum. Then it was assumed that the projections of the missing momentum and hadronic momentum into the ν-μ plane had the same direction. The magnitude of the missing momentum's projection was calculated by applying momentum balance transverse to the beam direction. The average correction to the visible energy was ~15%. Figure 3 shows the corrected neutrino energy distribution.

In principle the assignment of an event to reaction (1) or (2) can be done simply by examining the net charge of the event. In practice, however, as the visible-charge distribution of Fig. 4(a) shows, secondary interactions in the nucleus can alter the true charge. In particular, it is evident from Fig. 4(a) that there is a non-negligible number of events with visible charge exceeding +1.

To determine the number of events corresponding to reactions (1) and (2), we employed a simple technique similar to those used by other experiments[8,9] in heavy liquids. Let C_i represent the observed number of events with visible charge

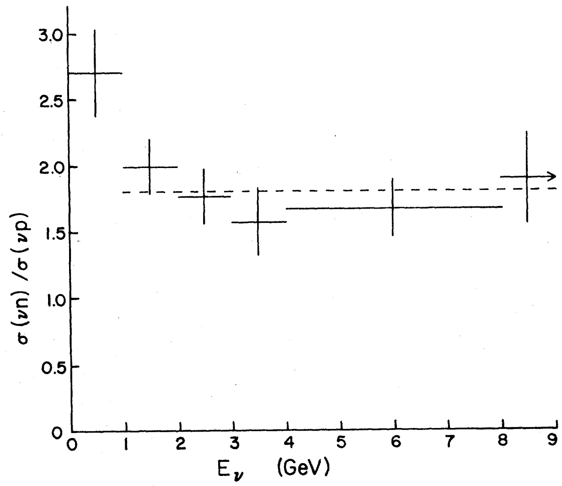

FIG. 5. The cross-section ratio $\sigma(\nu n)/\sigma(\nu p)$ for charged-current interactions as a function of incident neutrino laboratory energy. The dashed line indicates the value of the ratio for $E_\nu > 1$ GeV.

i. Let N_0, N_1, and N_h represent the actual number of events off neutrons in neon, protons in neon, and protons in hydrogen, respectively. Since the chamber liquid is 62% (atomic) neon, it follows that $N_h = 0.0613N_1$. Finally, we let P_j represent the probability that the true charge is altered by j units, and we consider the cases $j = -1$, 0, 1, and 2. We then solve the following set of equations:

$$C_{-1} = N_0 P_{-1}\,,$$
$$C_0 = N_0 P_0 + N_1 P_{-1}\,,$$
$$C_1 = N_0 P_1 + N_1 P_0 + N_h$$
$$C_2 = N_0 P_2 + N_1 P_1\,,$$
$$C_3 = N_1 P_2\,,$$
$$P_{-1} + P_0 + P_1 + P_2 = 1\,.$$

The cross-section ratio $R_{CC} = N_0/N_1$. For neutrino energies over 1 GeV, we obtain a raw value of 1.71 ± 0.18 for the ratio,[11] with $N_0 = 2279$, $N_1 = 1332$, and $N_h = 82$.

This calculated ratio requires a correction because, as mentioned previously, the charged-current sample includes a punchthrough background of 8.6%. This background consists of neutral-current events, and we make the correction assuming $R_{NC} = 1.0$. We justify this value later when we consider our neutral-current sample. We find that the correction to R_{CC} is less than 1 standard deviation.

Figure 5 shows the corrected value of R_{CC} as a function of neutrino energy. We note that an asymptotic value seems to be reached as early as 1 GeV. For neutrino energies over 1 GeV, we find $R_{CC} = 1.80 \pm 0.19$, where the error includes the statistical uncertainty, the uncertainty in the background correction, and an estimate of the uncertainty in the method used to deduce the true charge distribution. Our value is consistent with the prediction from the quark structure functions derived by Field and Feynman.

In order to define a neutral-current sample corresponding to reactions (3) and (4), we take all events that do not have a negative leaving track, and require that the total visible momentum make an angle less than 45° to neutrino beam direction. We obtain 1178 events in our neutral-current sample, and in Fig. 4(b) we display the visible-charge distribution for those events. It is clear that the shape of the distribution differs from that of the charged-current events. We calculate the cross-section ratio for the neutral-current events in the same manner as for the charged-current sample, obtaining a raw value of 1.27 ± 0.15 for R_{NC}, with $N_0 = 618$, $N_1 = 486$, and $N_h = 30$.

Our neutral-current sample contains a background due to incoming neutral cosmic rays. This background was low in the charged-current sample because the hadrons were unlikely to produce negative leaving tracks that would fake a μ^-. However, in the neutral-current sample the outgoing neutrino is not detected, and so we do not have a reliable discrimination against the background. To correct the ratio R_{NC} for the background, we need to determine the amount of the background and the value of the ratio for the background events.

To calculate the amount of the background, we use our charged-current sample. In our previous work using a narrow-band neutrino beam and the same detector, we found that the hadronic system has similar characteristics in charged- and neutral-current events at the same energy.[12] So we make a cut of 45° on the hadronic momentum in our charged-current events, obtaining a total of 2833 events. Using the world-average value[13] of 0.29 ± 0.01 for the neutral-to-charged-current ratio, we calculate[14] a background of 671 events in the neutral-current sample.

To determine the neutron-to-proton cross-section ratio for the background, we consider those events without negative leaving tracks which have the angle of the visible momentum greater than 60°. About 85% of these events represent cosmic-ray background, if the angular distribution of the hadronic momentum for neutral-current events is similar to that for charged-current events. We calculate the neutron-to-proton cross-section ratio for these events to be 1.42 ± 0.18, and then perform a background subtraction to obtain the corrected ratio for true neutral-current events. Our final result is

$$R_{NC} = \frac{\sigma(\nu n \to \nu + \text{hadrons})}{\sigma(\nu p \to \nu + \text{hadrons})} = 1.07 \pm 0.24 .$$

The fractional error on R_{NC} is larger than on R_{CC} primarily because of the uncertainties in the background subtraction procedure. We conclude that our measurement is entirely consistent with the value of unity expected from quark-model arguments.

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*Present address: Bell Laboratories, Holmdel, New Jersey 07733.

† Permanent address: Seton Hall University, S. Orange, New Jersey 07079.

‡Present address: Rutgers University, New Brunswick, New Jersey 08903.

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[11]The corresponding values of the charge-changing probabilities were $P_{-1} = 0.047$, $P_0 = 0.716$, $P_1 = 0.163$, $P_2 = 0.074$.

[12]C. Baltay *et al.*, Phys. Rev. Lett. 44, 916 (1980).

[13]C. Baltay, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Phys. Soc. of Japan, Tokyo, 1979), p. 882.

[14]The restricted charged-current sample contains a punchthrough background of 244 events, leaving 2589 true charged-current events. We therefore expect 751 true neutral-current events, of which 244 are present as punchthrough in the charged-current sample. This leaves 507 true neutral-current events in the neutral-current sample, yielding a background of $1178 - 507 = 671$ events.