setting up and running of this experiment. L. Holloway and C. Wang made important contributions in the early stages of the experiment. K. Gray, S. Marino, and G. Alverson provided indispensible technical expertise. The scanning and measuring staffs at Nevis Laboratory and the University of Illinois are thanked for their excellent work. Finally, we would like to thank Professor S. Adler and Professor C. Baltay for many interesting discussions.

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Measurement of the Ratio $\sigma_c(\bar{\nu}_\mu + N \to \mu^+ + X)/\sigma_c(\bar{\nu}_\mu + N \to \mu^- + X)$ at High Energy*

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Using a sample of 4994 neutrino events and 2408 antineutrino events we have measured the ratio of antineutrino to neutrino charged-current cross sections up to 100 GeV. Neutrino flux-independent and flux-dependent measurements were carried out with good agreement between the two methods. Below 30 GeV the ratio was found to be 0.38 ± 0.06. The cross-section ratio shows a significant departure from this value above 50 GeV.

The ratio of antineutrino to neutrino charged-current cross sections on isoscalar targets and at high energy is an important parameter in neutrino physics. Previous measurements have established a ratio of approximately 0.4 in the vicinity of 30 GeV and below in energy.[1-4] We report here a measurement of this ratio at higher energies.[5]

Neutrino and antineutrino events were collected in the Harvard-Pennsylvania-Wisconsin-Fermilab detector at Fermilab.[2,3,6] The cross-section ratio was determined by two independent techniques using two samples of data: (a) a sample of 2900 neutrino and 570 antineutrino events which were obtained from a run in a neutrino beam focused by quadrupole triplet (the "quadrupole-triplet beam"), in which both neutrino and antineutrino events were detected simultaneously[7]; (b) the full sample of 4994 neutrino and 2408 antineutrino events which were obtained using

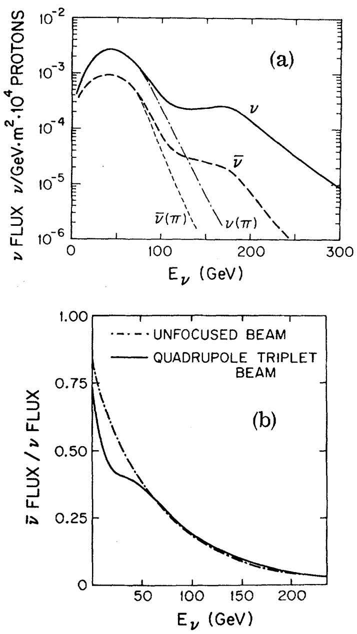

FIG. 1. (a) Calculated neutrino and antineutrino fluxes for the quadrupole-triplet neutrino beam obtained from the measured $\pi^{\pm}$ and $K^{\pm}$ fluxes from a thick target. (b) Ratios of the neutrino and antineutrino fluxes from the quadrupole-triplet beam and an unfocused neutrino beam for pion and kaon neutrinos.

both the quadrupole-triplet beam and a horn-focused beam. Sample (a) is used for a measurement of the ratio which depends on the knowledge of neutrino and antineutrino fluxes whereas sample (b) is used for a flux-independent determination of the ratio.

The quadrupole-triplet beam data were obtained with the primary proton energy of 380 GeV and with the quadrupole-triplet beam set to focus 200-GeV positive and negative secondaries.[7] The resulting neutrino and antineutrino spectra were determined using the measured yield of hadrons[8,9] and the focusing properties of the quadrupole-triplet beam. These spectra are shown in Fig. 1(a). The ratio of antineutrino to neutrino flux as a function of energy is shown in Fig. 1(b). The estimated systematic uncertainty in the flux ratio is approximately 10%. Also shown in Fig. 1(b) is the same ratio for an unfocused beam for comparison. We note that the salient features of flux determination for the quadrupole-triplet beam are the following: (1) The ratio of neutrino to antineutrino fluxes is similar to the ratio obtained from an unfocused beam above 30 GeV, indicating that it is not affected by the focusing properties of the quadrupole-triplet beam. (2) Pion neutrinos and antineutrinos dominate the fluxes up to ~ 80 GeV, an important factor in determining the $\bar{\nu}$ to ν cross-section ratio up to that energy since the π^+/π^- production ratio is better determined experimentally than the K^+/K^- ratio.

TABLE I. Correction for events that fall outside the acceptance of the detector, $N_{\text{corr}}{}^{\nu,\bar{\nu}} = N_{\text{obs}}{}^{\nu,\bar{\nu}}/\epsilon_{\nu,\bar{\nu}}$.

E_ν (GeV)	ϵ_ν	$\epsilon_{\bar{\nu}}$
10–30	0.56	0.88
30–50	0.75	0.96
50–70	0.82	0.98
70–90	0.86	0.99

The observed neutrino and antineutrino events were corrected for geometric inefficiency in a model-independent way that is described elsewhere.[10] In addition a small correction was applied to the data for events that fall outside the acceptance of the detector. This correction was calculated using Bjorken scaling which has been verified for energies below 30 GeV.[10] We emphasize that the magnitude of the correction is small at energies above 50 GeV as can be seen in Table I.

The ratio $\sigma_c(\bar{\nu})/\sigma_c(\nu)$ is then determined using the corrected number of ν and $\bar{\nu}$ events and the fluxes. Figure 2 shows the energy dependence of this ratio. At energies below 50 GeV the ratio is consistent within 1 standard deviation with previous measurements,[1-4] whereas at higher energies the cross-section ratio rises above 0.4.

The ratio of cross sections has also been determined in a flux-independent way using the full sample of neutrino and antineutrino data. The

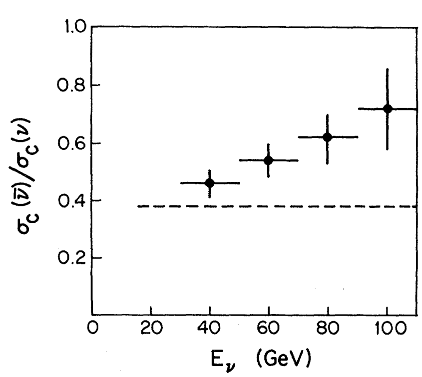

FIG. 2. Ratio of antineutrino to neutrino charged-current cross sections obtained from the quadrupole-triplet beam data as a function of neutrino energy. The dashed line is at the value $\sigma_c{}^{\bar{\nu}}/\sigma_c{}^{\nu} = 0.38$.

method is based on charge-symmetry invariance and the energy independence of quasielastic and N^* production cross sections at high energy; namely,

$$\sigma(\nu_\mu + T \to \mu^- + N \text{ or } N^*) = \sigma(\overline{\nu}_\mu + T \to \mu^+ + N \text{ or } N^*) \approx \text{const}, \quad (1)$$

where T is an isoscalar target. Figure 3(a) shows the $\sigma_c(\overline{\nu})/\sigma_c(\nu)$ ratio obtained from the quasielastic and N^* flux normalization. The small number of quasielastic and N^* events above 60 GeV prohibits a measurement of the ratio above this energy by this technique. We note that the lowest-energy measurement (below 30 GeV) is in very good agreement with previous measurements.[1,4] At higher energies there is no disagreement with the results of Ref. 3, if one takes into consideration the dependence of the measured cross-section ratios on the semiempirical neutrino and antineutrino fluxes used therein.

In order to extend the flux-independent measurement above 60 GeV and to obtain better statistical accuracy, we have adopted a technique based on charge-symmetry invariance.[11-13] This technique extends the quasielastic and N^* flux normalization to include events with higher W, where W is the recoiling hadronic mass in the inelastic collision.[13] In this case the technique is fundamentally related to the Lee and Yang theorem

$$\lim_{E\to\infty} \frac{d\sigma}{dW^2}(\nu_\mu + T \to \mu^- + \text{hadrons}) = \lim_{E\to\infty} \frac{d\sigma}{dW^2}(\nu_\mu + T \to \mu^+ + \text{hadrons}). \quad (2)$$

Sakurai has indicated the range of W values for which relation (2) is expected to hold to better than 15%.[13] Applying this technique to the data gives the ratio of cross sections shown in Fig. 3(b). Further variations of the W interval in an arbitrary way lead to consistent results with the Sakurai prescription as shown in Fig. 3(b). Table II shows the number of events for $W < W_{max}$ used to determine the flux, where W_{max} was determined by the Sakurai technique.[13] We have also investigated the effects of resolution smearing on the cross-section ratio and have found that the ratio is insensitive to these effects. The ratios of cross sections in Fig. 3(b) are consistent with those obtained using the quasielastic technique [Fig. 3(a)]; in both methods at higher energies the ratio is observed to rise significantly above

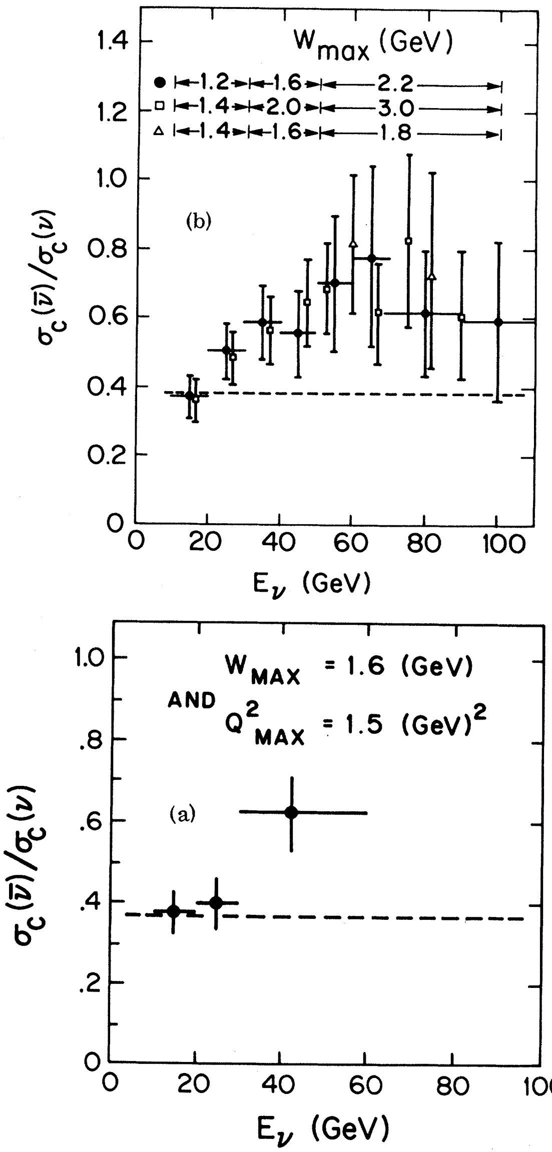

FIG. 3. (a) Ratio of antineutrino to neutrino charged-current cross sections obtained by the quasielastic flux normalization method. (b) Determination of the ratio of antineutrino to neutrino charged-current cross sections by the Sakurai flux-independent normalization prescription (black dots). W_{max} refers to the maximum hadronic recoil mass (W) that is used in the normalization procedure. The open triangle, circle, and square denote the value of the ratio that is obtained if W_{max} is varied as shown in the given energy intervals.

0.4. Systematic uncertainties in the flux determination by the two methods preclude a more detailed comparison, however.

We have found good agreement in the ratio $\sigma_c(\overline{\nu})/\sigma_c(\nu)$ as measured by these independent techniques. A growing ratio of cross sections

TABLE II. The number of events in each energy interval used in Sakurai flux normalization.

$E_{\nu,\bar{\nu}}$ (GeV)	W_{max} (GeV)/c^2)	$I^{\nu}=\int_0^{W_{max}}(dN/dW)^{\nu}dW$	$I^{\bar{\nu}}=\int_0^{W_{max}}(dN/dW)^{\bar{\nu}}dW$
10–20	1.2	57	151
20–30	1.2	78	97
30–40	1.6	81	61
40–50	1.6	64	34
50–60	2.2	61	24
60–70	2.2	43	13
70–90	2.2	45	17
90–110	2.2	29	9

with energy is indicated by the data, with the ratio exceeding 0.5 above 50 GeV. The changing ratio of cross sections is presumably directly related to the high-y anomaly reported previously.[4, 10, 14] We note that the cross-section ratio measurement at the highest energies is somewhat inconsistent with the results reported in Ref. 5.

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