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$\bar{\nu}_\mu$ NUCLEON CHARGED CURRENT TOTAL CROSS SECTION FOR 5–250 GEV

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Abstract

The $\bar{\nu}_\mu$ charged-current total cross section has been measured using the FERMILAB 15 ft. bubble chamber plus the External Muon Identifier and Internal Picket Fence. Beam monitoring information used for the flux calculation was obtained from the CCFRR collaboration, whose detector operated in the same dichromatic beam. Our (E388) result, averaged over $\bar{\nu}_\mu$ energies from 5-250 GeV, is $\sigma/E = 0.340 \pm 0.019 \pm 0.022 \times 10^{-38}$ cm^2/ GeV/nucleon for an isoscalar target.

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The total cross sections for ν_μ and $\overline{\nu}_\mu$ charged–current (CC) interactions are of fundamental importance in the understanding of weak interactions and the structure of nucleons. Interest in these cross sections has recently been heightened by a new measurement [1] which yields values of σ/E about 15% higher than previous results [2–5]. This paper presents results on the total cross section for $\overline{\nu}_\mu$ CC interactions by FERMILAB experiment E388 using the 15 ft. bubble chamber filled with a heavy Ne/H_2 mixture and exposed to the same dichromatic $\overline{\nu}_\mu$ beam as the counter experiment of reference [1]. The External Muon Identifier (EMI) [6] and the Internal Picket Fence (IPF) were used in the selection of CC events. The $\overline{\nu}_\mu$ flux through the bubble chamber was obtained from measurements of the parent beam flux (predominantly pions and kaons) taken by the CCFRR collaboration [1,7–8] combined with a beam transport and decay Monte Carlo program.[9]

The primary beam of 400 GeV protons impinging upon a 12 in. BeO target produced a secondary particle flux predominantly of pions and kaons. The FERMILAB N-30 magnet train selected and focussed negatively charged secondaries at one of five momentum tunes between 120 and 250 GeV/c and directed this secondary beam into the evacuated decay pipe towards the neutrino detectors. A beam collimating slit, located near the end of the train, could be closed to allow measurement of the event rates due to neutrinos produced upstream of the decay pipe. The secondary beam intensity, position, and constituent particle fractions ($e/\pi/K/p$ ratios) were measured by CCFRR at the expansion port using ion chambers and a Cerenkov counter. For runs with negative secondaries, the estimated error in the total flux from the ion chamber calibration was 5.5% . The calibration of the Cerenkov counter led to uncertainties of about 1% in the pion fractions and 4% in the kaon fractions. For more details of these calibrations see references [7–8]. We have relied on the CCFRR data tapes, which contain the bubble chamber roll and frame numbers, to obtain the ion chamber counts for frames with well–steered (within 5 cm of the central position) beam. Only such frames (135,000 total) were used in the cross section determination.

The 15 ft. bubble chamber was filled with a Ne/H_2 mixture of density 0.67 ± 0.01 gm/cm^3 (0.72 mole fraction neon or 0.56 atomic) with a radiation length of 45 cm. The density was obtained using a sample of 123 stopping protons whose momenta determined from curvature had errors less than 5% . This value is in good agreement with that determined by averaging the results of chromatographic analyses of samples of the chamber liquid taken near the beginning and end of the run. (Addition of neon after our run resulted in a higher density for the ν_μ exposure of E380[10].) Limiting the vertical coordinate z to be within ± 100 cm of the chamber center and requiring a minimum potential length of 50 cm (the distance to the downstream chamber wall) yields a total fiducial volume of 15.1 m^3 and a total fiducial mass of 10.1 metric tons.

An important feature of this experiment is the IPF, an array of 24 counters each 10 cm wide and 240 cm high located inside the vacuum tank between the downstream bubble chamber wall and the magnet coils. The IPF provides timing information due to hits from charged hadrons and electrons as well as from muons. The efficiency for at least one IPF counter to fire was determined to be 48% for through–muons (single muons traversing the entire chamber) and 88% for $\bar{\nu}_\mu$ CC events occurring in the chamber. The high IPF efficiency has allowed us to do an independent check of the scanning efficiency for CC events.

After the film was scanned with very general scanning and measuring criteria, 4200 neutral particle induced interactions, including one-prong events, were selected for measurement. The measuring criteria were designed to include events with energy as low as 1 GeV and indeed most of the measured events have energies below 2 GeV. The scanning efficiency was determined by two independent methods. First, 40% of the film was double scanned. A second method for detecting CC events (and also for detecting any possible insensitivity of the bubble chamber) was to use three–fold time coincidences in the two EMI planes and the IPF, corresponding to muons that came from the bubble chamber. Frames with such coincidences were checked for events in 50% of the film. Events found with this method were not biased by track visibility on the film, so the method provided an important check of the scanning efficiency. No significant difference was found in the computed first scan efficiency for CC events between film rescanned and film checked by the EMI/IPF coincidence method. The resulting first scan efficiency obtained from these two methods is $91 \pm 2\%$ for CC events with total visible momentum greater than

5 GeV/c. The combined efficiency with the inclusion of events found only in the second scan and those found only by the EMI/IPF coincidence method is 98.6 ± 0.3% . This efficiency includes one-prong events with 3 or more primary γ's but excludes those with 2 or fewer primary γ's. These latter events are very difficult to distinguish from through–muons and have an efficiency for three-fold EMI/IPF coincidences of only about 50% . We estimate our overall efficiency for such events to be 39 ± 10% and make a 1.3 ± 0.9% correction to our total observed event rate based on the 3 such events detected. This correction is consistent with what would be expected assuming constant cross sections for the $\mu^+ n$[11] and $\mu^+ n\pi^0$ (assumed the same as $\mu^+ p\pi^-$[12]) final states.

Our sample of CC events was selected by requiring a muon to be a primary track that leaves the chamber without interacting, has a momentum of at least 4 GeV/c, and has a two-plane match in the EMI of confidence level greater than 10^{-4}. Muon misidentification from hadronic decays and punchthrough of hadrons into the EMI was estimated to be 0.03% , which is negligible for this analysis. Events were lost due to EMI electronic inefficiency, to muons that miss the EMI, and to muons with momenta below 4 GeV/c. The average two–plane electronic efficiency, obtained using individual chamber efficiencies (typically 96%) weighted by the distribution of EMI hits from $\bar{\nu}_\mu$ interactions, is 92.9 ± 0.7%. To determine the geometrical acceptance of the EMI, real events were moved around the chamber (in the computer!) at constant radius from the beam center, varying the azimuthal angle and longitudinal position of the event vertex. By also rotating the muon momentum vector around the $\bar{\nu}_\mu$ direction, many combinations of vertex position and muon direction were used to calculate the fraction of such muons which would pass through the two planes of the EMI. In this way the total geometrical acceptance of the EMI for μ^+ of momenta above 4 GeV/c is determined to be 97.6 ± 0.9% . The corresponding acceptance for μ^- is 71% due to the asymmetry of the EMI and softer μ^- momentum spectrum. The EMI acceptance as a function of $\bar{\nu}_\mu$ energy was also determined using real events. The energy–dependent fraction of events having muons of momenta above 4 GeV/c was determined from Monte Carlo[13] events and is 0.981 ± 0.003 for the entire sample. There are also two energy–independent corrections for frames for which EMI data is not available or for which the EMI timing is bad (3.6%) and for EMI dead time

(0.4%). Detailed checks indicate no evidence for bubble chamber or EMI insensitivity and result in an upper limit of 3% for losses due to these sources. Other possible event losses have also been investigated and none has been found to be significant.

Finally, there is a subtraction due to backgrounds from $\bar{\nu}_\mu$ produced upstream of the decay region and by $K_{\mu 3}$ decays in the decay region. (The flux calculation used below does not include such $\bar{\nu}_\mu$.) The prompt background is that due to neutrinos from decays of short-lived particles produced in the target and is calculated using BEBC beam dump results.[14] The wideband background results from particles produced in the first magnet downstream of the target, where most of the secondary beam interacts, and is calculated from the corrected number of ν_μ events (with the small prompt contribution subtracted) by multiplying by 0.3 to get the corresponding number of $\bar{\nu}_\mu$ events. The factor of 0.3 results from a Monte Carlo simulation, using the program NUBEAM[15], of the decays of particles produced in the first magnet. The wideband $\bar{\nu}_\mu$ background calculated in this way is consistent with that determined by the CCFRR group, which uses their measured event rate with the beam collimating slit closed. (Decays of particles in the train, which contribute $< 1\%$ of the energy-weighted $\bar{\nu}_\mu$ flux from pion decays and 0.5–3.0% of that from kaon decays, contribute to the overall flux we calculate but are part of the CCFRR closed-slit background.) The background from $K_{\mu 3}$ decays is calculated using the same Monte Carlo program[9] used to calculate the $\bar{\nu}_\mu$ fluxes due to two-body pion and kaon decays.

Of the 356 $\bar{\nu}_\mu$ CC interactions passing the EMI, momentum, and fiducial volume cuts, 308 have CCFRR monitor data indicating well-steered beam. After subtracting backgrounds (7.1 events) and dividing by selection efficiencies (0.831 $\pm$0.014 overall), the total corrected number of $\bar{\nu}_\mu$ CC events is determined to be 362 $\pm$ 22 .

We assume that the cross section per nucleon is proportional to the $\bar{\nu}_\mu$ energy $E_{\bar{\nu}}$ and determine the proportionality constant, which we refer to as σ/E , using

$$\sigma^{cc}_{\bar{\nu}_\mu}/E_{\bar{\nu}} = \frac{(1-f)N(E_{\bar{\nu}})}{N_A \rho \int D(y,z)\,\phi(E_{\bar{\nu}},y,z)\,dy\,dz}$$

where $N(E_{\bar{\nu}})$ is the corrected number of $\bar{\nu}_\mu$ CC events of energy $E_{\bar{\nu}}$, ρ is the chamber liquid density, D(y,z) is the depth of liquid in the beam direction at the horizontal (y) and vertical (z) bubble chamber coordinates, $\phi(E_{\overline{\nu}}, y, z)$ is the energy-weighted $\overline{\nu}_\mu$ flux, N_A is Avogadro's number, and f is a 0.93% correction (due to the 2.8% proton excess) necessary to convert to an isoscalar-target cross section.

The corrected number of events $N(E_{\overline{\nu}})$ was determined using energy-dependent corrections for EMI acceptance, loss of events with μ^+ momenta below 4 GeV/c, and backgrounds. The correction for bubble chamber energy resolution was calculated in the Monte Carlo event simulation program and affects only the bin to bin comparison of the cross section, not the overall value for σ/E presented below. The systematic error in the energy resolution correction is typically 5% . The values presented in Fig. 1 result from combining data at different tunes and rebinning in terms of $\overline{\nu}_\mu$ energy. We do not give a value based on the 15 observed events in the 5–25 GeV range because of large statistical and systematic errors.

The energy-weighted $\overline{\nu}_\mu$ flux for two-body pion and kaon decays, $\phi(E_{\overline{\nu}}, y, z)$, was calculated using the beam transport and decay computer program[9], normalizing to the total number of particles at the expansion port and using the pion and kaon fractions determined by the CCFRR collaboration. The program parameters were adjusted by CCFRR so that the calculated central momenta and other beam parameters coincided with the measured values.[7] The estimated uncertainty in the flux and beam composition is about 6% , which is the same for both experiments.

Our value for σ/E for the entire energy range, 5–250 GeV, is $0.340 \pm 0.019 \pm 0.022 \times 10^{-38}$ cm^2 /GeV/nucleon, where the first error is statistical and the second is systematic. The systematic error is a combination in quadrature of a ± 0.020 uncertainty due to measurement of the numbers of pions and kaons at the expansion port and to the flux calculation plus ± 0.008 associated with the bubble chamber density and corrections for selection efficiencies. This σ/E value is somewhat higher than preliminary values given previously[16,17] due to improved values for various efficiencies, use of a smaller fiducial volume, and use of the complete sample of events including those found only in the second scan or by the EMI/IPF coincidence method. Our overall value of σ/E is in good agreement with that obtained by the CCFRR group [1] but is not significantly higher than previous results [2–5].

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experiment. We especially acknowledge the assistance of the Fermilab 15 ft. bubble chamber crew. We are grateful to the CCFRR collaboration for providing us with their data and for many useful discussions. This work was supported in part by the U. S. Department of Energy and National Science Foundation.

Figure Captions

Figure 1. Values of σ/E as a function of energy for this experiment (triangles) compared to CCFRR[1] (circles). The inner error bars represent statistical errors; the outer error bars represent systematic point–to–point errors. An overall systematic error of 5.5% is not indicated.

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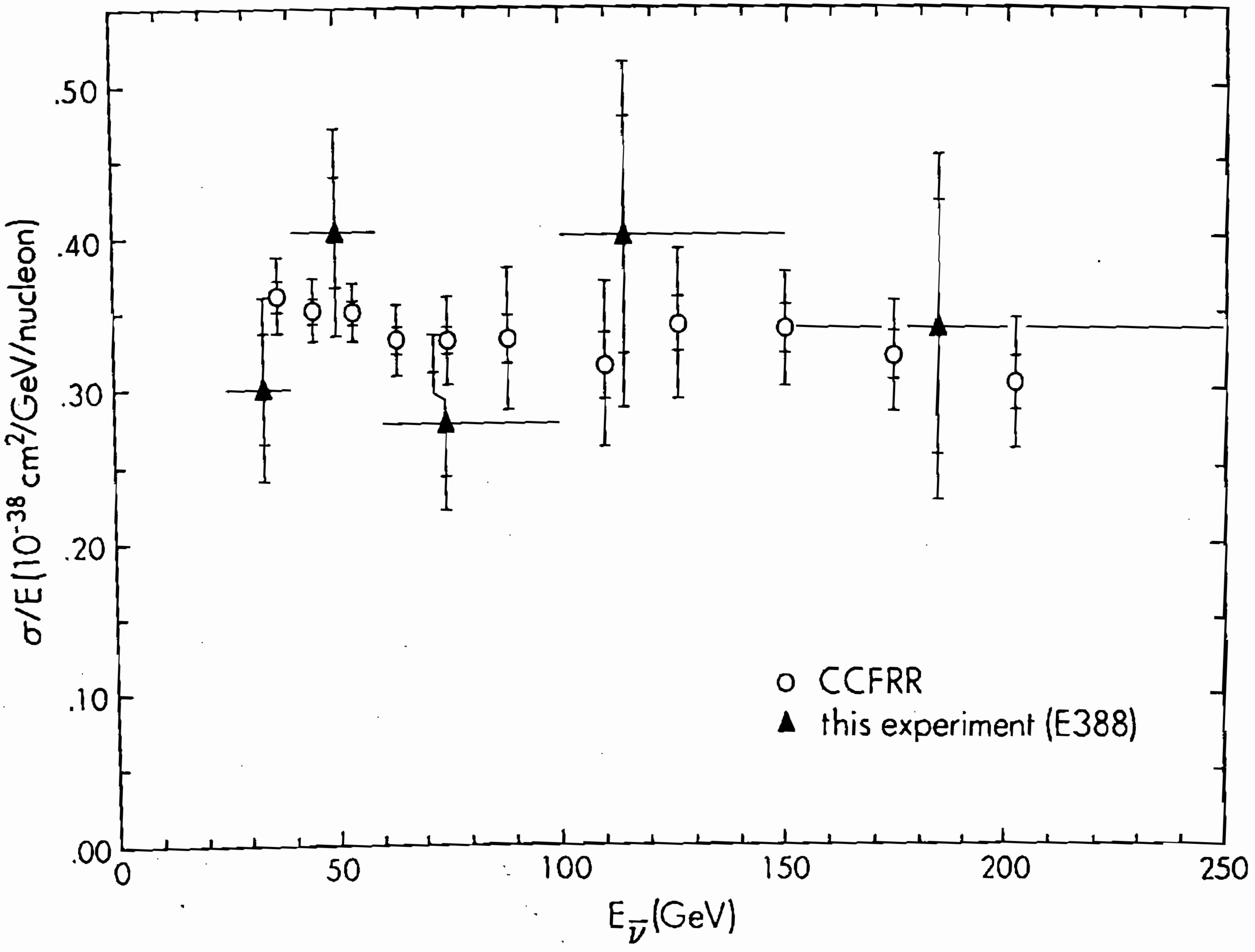

.50
.40
.30
.20
.10
.00
0
50
100
150
200
250
$\sigma/E\,(10^{-38}\,\mathrm{cm}^2/\mathrm{GeV/nucleon})$
$E_{\bar{\nu}}$ (GeV)
○ CCFRR
▲ this experiment (E388)

Fig. 1