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MEASUREMENT OF TOTAL CROSS SECTIONS FOR NEUTRINO AND ANTINEUTRINO CHARGED CURRENT INTERACTIONS IN HYDROGEN AND NEON

BEBC WA21 Collaboration

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ABSTRACT

BEBC filled in turn with hydrogen, and with a neon-hydrogen mixture, was exposed to the CERN SPS wide band neutrino and antineutrino beams. The ratios of the charged current cross sections per nucleon, $\sigma(\nu H_2)/\sigma(\nu Ne)$ and $\sigma(\bar{\nu} H_2)/\sigma(\bar{\nu} Ne)$, between 20 and 300 GeV were found to be 0.656 ± 0.017 and 1.425 ± 0.049, respectively. Multiplying these ratios by the revised cross sections in neon, $\sigma(\nu Ne)/E = (0.723 \pm 0.038) \times 10^{-38}$ cm^2/GeV per nucleon and $\sigma(\bar{\nu} Ne)/E = (0.351 \pm 0.019) \times 10^{-38}$ cm^2/GeV per nucleon, yields values for the total charged current cross sections on protons, $\sigma(\nu p)/E$ and $\sigma(\bar{\nu} p)/E$, of $(0.474 \pm 0.028) \times 10^{-38}$ cm^2/GeV and $(0.500 \pm 0.032) \times 10^{-38}$ cm^2/GeV respectively, and a value for the ratio $\sigma(\bar{\nu} p)/\sigma(\nu p)$ of 1.053 ± 0.063.

The aim of this analysis was to determine the total charged current cross sections for neutrino and antineutrino interactions on protons with the smallest possible systematic uncertainties. This was achieved by making a precise comparison of the cross sections in hydrogen and neon, and then using the cross sections in neon measured in the Narrow Band neutrino Beam (NBB), which has smaller flux normalisation uncertainties than the Wide Band Beam (WBB), to deduce the cross sections on protons.

The data used in the comparison come from exposures of the Big European Bubble Chamber (BEBC), filled with hydrogen (WA21) and with a 75 mole percent neon-hydrogen mixture (WA59), to the same wide band neutrino and antineutrino beams generated by 400 GeV protons from the CERN SPS. The four data sets were completely reanalysed for this investigation, so that every source of systematic error was either eliminated or corrected for.

To ensure that the geometries, beam spectra and muon identification criteria and acceptances were identical for the hydrogen and neon experiments, the following selection criteria were applied to all events:

(a) The vertex of the event was required to lie within the overlap of the fiducial volumes used by the two experiments.

(b) Identical beam conditions were selected for the hydrogen and neon runs. Beam constancy throughout the runs was ensured with the aid of the array of muon flux detectors distributed in the shielding [1]. All pulses for which the shape of the muon flux distribution was not in accord with a chosen standard were eliminated from the analysis.

(c) The charged current events were identified using the same External Muon Identifier (EMI) [2]. The performance of each wire in the EMI was monitored regularly using cosmic rays: the condition of the EMI was found to be the same for the four runs. The data from each experiment were processed using the same muon identification programme. All events were required to have a muon of the correct charge (i.e. μ^- for neutrino scattering and μ^+ for antineutrino scattering) and of momentum greater than 5 GeV/c.

(d) In the WA21 experiment very few of the neutral particles, other than V^os (i.e. K^os or Λ^os), were detected; so to avoid biases between the treatment of the hydrogen and neon data, all detected neutrals other than V^os were rejected in all four data sets. Then, for all events, the minimum possible energy E_{min} of the neutrino was calculated from

$$E_{min} = \frac{W^2_{min} - M^2_p - M^2_\mu + 2M_p E_\mu}{2(M_p + p^L_\mu - E_\mu)} \qquad (1)$$

where the minimum squared invariant mass of the final state hadron system W^2_{min} was set equal to M^2_p; M_p is the proton mass, and M_μ, E_μ and p^L_μ are respectively the mass, energy and longitudinal momentum with respect to the neutrino direction of the muon in the laboratory system. The actual energy of the neutrino was estimated using the formula

$$E' = p^L_\mu + \frac{<p^T_\mu>}{<p^T_{CH}>} p^L_{CH} \qquad (2)$$

where p^L_{CH} is the longitudinal momentum of the charged hadron system, (including any V^o s), in the event, and p^T_μ and p^T_{CH} are the transverse momenta relative to the beam direction of the muon and charged hadron system, respectively, in the lepton plane. The factor $<p^T_\mu>/<p^T_{CH}>$ was calculated separately for each data set, the averages being taken over all events other than one-prongs, i.e. reactions of the type $\bar{\nu}p \rightarrow \mu^+$ + neutrals. The values of $<p^T_m>/<p^T_{CH}>$ for the data sets νp, νNe, $\bar{\nu}p$, $\bar{\nu}Ne$ were 1.501, 1.646, 1.550, 1.746, respectively(*). The neutrino energy E was then taken to be the larger of E_{min} and E'. For each event E was required to be greater than 20 GeV and less than 300 GeV.

(*) These factors are larger for antineutrinos and for neon mainly because of the higher probability of the final state baryon being an undetected neutron; in addition in neon some energy is absorbed in breaking up the nucleus.

Corrections due to the following sources of experimental bias were then applied to each data set:

(a) The imperfect geometrical acceptance of the EMI.

(b) The scan inefficiency, which was calculated separately for each experiment and for each event topology.

(c) The proportion of events with muon momentum less than 5 GeV/c.

(d) The smearing effect due to the poor resolution in the measurement of the neutrino energy.

(e) The background due to neutral current (NC) events mis-identified as charged current events.

The scan efficiencies for events with five or more charged tracks at the primary vertex were better than 99% for all data sets, but were smaller for lower multiplicities; in particular, events of the one-prong topology proved extremely difficult to find. In both experiments special scans were performed to search for events of this type, and to determine the scan efficiencies for all multiplicities.

In the WA59 experiment two independent scans of the whole film were conducted. These were followed by two special scans in the antineutrino film in which all muons leaving the bubble chamber were tracked back until they were seen to either enter the chamber or originate in an interaction in the liquid. Two further special scans in a reduced fiducial volume were then performed to establish the scan efficiencies for the various topologies.

In the WA21 experiment antineutrino data taken after the installation of the Internal Picket Fence, (IPF) [3], were used to determine the scanning efficiencies. The leaving point of the muon in a charged current event in the liquid was predicted by correlating hits in the downstream portion of the IPF, and the inner and outer planes of the EMI. Two independent scans were then performed, guided by the predictions. The antineutrino beam for the pre-IPF and IPF runs was the same, so the assumption that the multiplicity distributions for these data sets be invariant was used to calculate the scanning efficiencies for the pre-IPF data used in this analysis. Since the pre-IPF data contain so few one-prongs, events of this topology found in the IPF runs were added to the data sample and weighted to ensure that the correct multiplicity distribution was obtained. For the hydrogen experiment, the neutrino and antineutrino films used in this analysis were scanned in parallel in the same laboratories, so the scanning efficiencies for a given event topology were assumed to be the same for the neutrino and antineutrino data.

The corrections for the muon momentum cut and the energy smearing were calculated separately for each data set using a Monte-Carlo computer programme written to simulate the WA21 and WA59 experiments. The corrections to the raw event numbers from all the above sources are shown in table 1.

The ratio of the total charged current cross sections per nucleon is given by

$$\frac{\sigma(H_2)}{\sigma(Ne)} = \frac{N_{H_2}\,\rho_{Ne}\,\Phi_{\mu Ne}}{N_{Ne}\,\rho_{H_2}\,\Phi_{\mu H_2}} \qquad (3)$$

where the symbols H_2 and Ne refer to the hydrogen and neon-hydrogen targets respectively, N is the corrected number of events, ρ is the liquid density and Φ_μ is the muon flux, which is proportional to the neutrino flux, recorded by identical detectors in each experiment and summed over all frames used. The ratio of the liquid densities ρ_{Ne}/ρ_{H_2} was measured to be 11.26 ± 0.11, and the ratio of muon fluxes $\Phi_{\mu Ne}/\Phi_{\mu H_2}$ was measured to be 0.140 ± 0.001 for the neutrino data and 0.459 ± 0.005 for the antineutrino data. The ratio of the cross section per nucleon on hydrogen, $\sigma(p)$, to that on an isoscalar target, $\sigma(I)$ is:

$$\frac{\sigma(p)}{\sigma(I)} = \frac{2(A - Z)}{A - 2Z + A\,\dfrac{\sigma(Ne)}{\sigma(H_2)}} \qquad (4)$$

where A is the number of nucleons and Z the number of protons in the neon-hydrogen mixture.

The following values for the ratios of the total charged current cross sections per nucleon were thus obtained:

$$\begin{aligned} \frac{\sigma(\nu p)}{\sigma(\nu I)} &= 0.656 \pm 0.015\ (\text{stat.}) \pm 0.008\ (\text{syst.}) \\ \frac{\sigma(\bar{\nu} p)}{\sigma(\bar{\nu} I)} &= 1.425 \pm 0.030\ (\text{stat.}) \pm 0.039\ (\text{syst.}) \end{aligned} \tag{5}$$

For the antineutrino case, the dominant source of systematic error is the uncertainty in the scanning efficiencies for the events with low prong topologies.

In table 2 the values for the cross section ratios from this analysis are compared with similar measurements from other experiments; all values shown have been corrected for the non-isoscalarity of the target. Table 3 shows the values of the ratios from this analysis as a function of (anti) neutrino energy. The first error is statistical, and the second is the result of combining the systematic errors from all sources in quadrature. Also added to table 3 are the values of the ratios for E less than 20 GeV, which are not included elsewhere.

The total charged current cross sections on protons were then calculated by multiplying the ratios (5) by the isoscalar-corrected total cross sections measured by the WA47 collaboration [4] for charged current νNe and νNe interactions above 20 GeV using the narrow band neutrino beam, in which the neutrino flux was measured directly from the associated muon flux. These cross sections have been revised [5] since publication for two reasons, based on recently gained additional information:

(a) From the above mentioned special scans performed during the analysis of the WA59 data it was found that the event samples used in the WA47 analysis were underestimated due to the loss of events with low prong topologies. Correcting for this additional scanning inefficiency increases the neutrino and antineutrino cross section values by 1.8% and 7.5% respectively.

(b) From measurements made in the recent narrow band neutrino beam experiments at CERN, it was found that the absolute muon fluxes used in the WA47 analysis were overestimated. Correcting for this effect increases the neutrino and antineutrino cross section values by 2.1% and 0.9% respectively.

The revised values are:

$$\frac{\sigma(\nu I)}{E} = (0.723 \pm 0.013 \pm 0.036) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\ \text{per nucleon}$$

$$\frac{\sigma(\bar{\nu} I)}{E} = (0.351 \pm 0.010 \pm 0.019) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\ \text{per nucleon} \qquad (6)$$

$$\frac{\sigma(\bar{\nu} I)}{\sigma(\nu I)} = 0.485 \pm 0.017 \pm 0.011$$

From the values (5) and (6) the total cross sections on protons are:

$$\frac{\sigma(\nu p)}{E} = (0.474 \pm 0.014 \pm 0.024) \times 10^{-38}\mathrm{cm}^2/\mathrm{GeV}$$

$$\frac{\sigma(\bar{\nu} p)}{E} = (0.500 \pm 0.018 \pm 0.027) \times 10^{-38}\mathrm{cm}^2/\mathrm{GeV} \qquad (7)$$

$$\frac{\sigma(\bar{\nu} p)}{\sigma(n p)} = 1.053 \pm 0.049 \pm 0.040$$

In table 4 these measurements are compared with measurements of the same quantities from other experiments. Also shown in the table are the targets used for the various measurements and the method used to normalise them, (i.e. via the Wide Band Beam flux (WBB) or via an isoscalar cross section measured using the Narrow Band Beam (NBB)).

In conclusion, the charged current total neutrino and antineutrino cross sections per nucleon in hydrogen and in a neon-hydrogen mixture have been compared under identical experimental conditions. The resulting ratios have been multiplied by the revised total cross sections on neon measured in the narrow band beam, which has smaller flux uncertainties than the wide band beam, thus obtaining the total cross sections on protons with a precision of 6%.

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TABLE 1

The corrections to the raw event numbers

Data set	νp	νNe	$\bar{\nu} p$	$\bar{\nu} Ne$
Raw event numbers	2666	6164	2426	10466
EMI acceptance weight	+ 32	+ 118	+ 13	+ 82
NC background weight	− 16	− 13	− 7	− 21
Correction for 1-prong losses	−	+ 25(a)	+ 473	+ 214
Correction for > 1-prong losses	+ 96	+ 255	+ 133	+ 359
Muon momentum cut correction	+ 48	+ 140	+ 55	+ 159
Smearing correction	+ 358	+ 888	+ 130	+ 598
Corrected event numbers	3184	7577	3223	11857

(a) 1-prongs in ν Ne interactions arise when the final state hadrons are absorbed or are neutral and escape detection.

TABLE 2

The cross section ratios

Experiment	$\frac{\sigma(\nu p)}{\sigma(\nu I)}$	$\frac{\sigma(\bar{\nu} p)}{\sigma(\bar{\nu} I)}$
This analysis	0.656 ± 0.015 ± 0.008	1.425 ± 0.030 ± 0.039
BEBC-TST (I = Ne) [6]	0.694 ± 0.043 ± 0.010	1.23 ± 0.11 ± 0.02
CDHS (I = Fe) [7](a)	0.65 ± 0.02	1.28 ± 0.08

(a) The values quoted here have been corrected for the non-isoscalarity of the target.

TABLE 3

The total charged current cross section ratios as a function of energy

Energy (GeV)	$\langle E_\nu \rangle$	$\frac{\sigma(\nu p)}{\sigma(\nu I)}$	$\langle E_{\bar\nu} \rangle$	$\frac{\sigma(\bar\nu p)}{\sigma(\bar\nu I)}$
< 20	14	0.671 ± 0.034 ± 0.009	13	1.480 ± 0.067 ± 0.051
20-30	23	0.668 ± 0.033 ± 0.008	23	1.561 ± 0.065 ± 0.047
30-50	37	0.629 ± 0.027 ± 0.008	36	1.406 ± 0.055 ± 0.037
50-80	60	0.613 ± 0.032 ± 0.008	60	1.304 ± 0.068 ± 0.032
80-120	95	0.727 ± 0.042 ± 0.009	92	1.317 ± 0.098 ± 0.031
120-180	139	0.716 ± 0.053 ± 0.009	137	1.276 ± 0.158 ± 0.034
180-300	196	0.642 ± 0.081 ± 0.008	195	1.457 ± 0.445 ± 0.020
20-300	62	0.656 ± 0.015 ± 0.008	46	1.425 ± 0.030 ± 0.039

TABLE 4

The total charged current cross sections on protons (in 10^{-38} cm^2/GeV)

Target	Normalisation	$\frac{\sigma(\nu p)}{E}$	$\frac{\sigma(\bar\nu p)}{E}$
This analysis	NBB-Ne	0.474 ± 0.014 ± 0.024	0.500 ± 0.018 ± 0.027
hydrogen [6]	NBB-Ne(a)	0.502 ± 0.032 ± 0.026	0.432 ± 0.041 ± 0.021
deuterium [8]	WBB muon flux	0.40 ± 0.04	0.44 ± 0.03
hydrogen [7,9]	NBB-Fe(b)	0.44 ± 0.02	0.44 ± 0.03

(a) The values quoted here are normalised to the revised NBB-Ne cross sections used in this analysis.

(b) The values quoted here are normalised to the NBB-Fe cross sections of ref. [9].