RL-83-059

Science and Engineering Research Council
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July 1983

RL-83-059

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A COMPARISON OF CHARGED CURRENT CROSS-SECTIONS AND STRUCTURE FUNCTIONS
FOR NEUTRINO AND ANTINEUTRINO BEAMS ON HYDROGEN AND NEON

BEBC TST Neutrino Collaboration

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ABSTRACT

Using BEBC equipped with a hydrogen-filled neon-surrounded track sensitive target, the charged current cross sections and structure functions of hydrogen and neon targets traversed by the same neutrinos and antineutrinos are compared directly. The measured total cross section ratios between hydrogen and neon allow precise total cross section values for hydrogen to be inferred. Using this normalisation, the ν and $\bar{\nu}$ hydrogen data are combined and the quark distributions in free nucleons, parametrised as functions of ξ , are extracted. This free-nucleon parametrisation is then compared directly with the neon data in order to measure nuclear effects such as those recently reported by the EMC collaboration. Only small effects are seen, in excellent agreement with recent SLAC data in a more similar A and q^2 range.

1. INTRODUCTION

Total cross-sections for charged current interactions of ν and $\bar{\nu}$ with heavy targets such as neon or iron are well measured using narrow band beams⁽¹⁾. Correspondingly precise values for free proton targets cannot be obtained, however, because adequate event rates require wide band beams where the systematic errors in determining the ν and $\bar{\nu}$ fluxes are larger. BEBC equipped with a hydrogen-filled track sensitive target (TST) surrounded by a neon-hydrogen mixture provides substantial visible volumes of hydrogen and of neon that are traversed by identically the same neutrinos. The event rates in these volumes can therefore be compared directly to give total cross-section ratios between hydrogen and neon targets that have negligible systematic errors. Our earlier results⁽²⁾ did not include any $\bar{\nu}$ data, used fewer ν interactions on hydrogen and included extra ν interactions on neon in which only the μ^- was measured.

The events used in this analysis were fully measured. The cross-sections can therefore be compared differentially as a function of Bjorken x or Nachtmann ξ and a full set of quark and antiquark functions extracted. The previous analysis⁽²⁾ used x but here we prefer to use ξ ($\xi = 2x/(1 + (1 + 4m^2 x^2/q^2)^{1/2})$, $m = \text{mass of proton}$). This is for two reasons.

Firstly, our data are mainly at low q^2 but the use of the ξ variable is known to absorb target mass corrections and thereby to remove much of the q^2 dependence observed at low q^2 . Secondly, our $\bar{\nu}$ distributions require correction for unseen 1-prong channels and, since the ξ distributions of the seen and unseen channels differ much less than do their x distributions, using ξ considerably reduces our sensitivity to this correction.

With certain assumptions the distributions in ξ of the u and d quarks in the nucleon can be extracted from the hydrogen distributions alone. The neon distributions can then be predicted ignoring nuclear binding. Comparing these predictions with the neon data provides a test for nuclear effects. Such effects have previously been reported in comparisons of muon and electron scattering on deuterium with iron and aluminium^(3,4,5).

2. EXPERIMENTAL DETAILS

For this experiment, BEBC was equipped with a 3m^3 Track Sensitive Target. This consisted of a flexible-walled transparent lexane box, 1.4m wide x 0.97m deep x 2.45m long in the beam direction. It was filled with liquid hydrogen, the rest of BEBC being filled with a heavy neon-hydrogen mixture. Both liquids were at almost the same temperature (29.4°K) and rendered track sensitive at almost the same expanded pressure by the action of the main chamber piston. Early in the run some neon entered the hydrogen filling of the TST via a supply-line leak. Thereafter a small overpressure was maintained inside the TST to reverse the leak. The neon concentration thus fell slowly during the course of the run from 77 mole% to 68 mole%.

The experiment, WA24, was carried out using the standard CERN-SPS wide band $\nu(\bar{\nu})$ beam with mean $\nu(\bar{\nu})$ energy $27.5(23.8)$ GeV produced by $350(330)$ GeV protons from the SPS. A total of 250,000 neutrino and 270,000 antineutrino pictures were taken, mostly in double-pulsing mode alternating with hadron-beam pictures.

The ν and $\bar{\nu}$ beam conditions were continuously recorded by the neutrino flux monitoring (NFM) system. This consists mainly of arrays of solid state detectors placed in gaps at several different depths in the shielding. These measure the local fluxes of muons produced by the same π^+ and K^+ decays that give rise to the neutrinos and antineutrinos. Provided their readings remain proportional to each other, confirming that beam conditions are stable, they are therefore also proportional to the neutrino and antineutrino fluxes through the fiducial volume.

Data from the 2-plane external muon identifier (EMI) were recorded throughout the run. Our previous analysis⁽²⁾ relied solely on the EMI to identify the charged current events in the standard way. Here we present instead a kinematical selection method that is monitored and cross-checked using EMI-selected control samples. It has been checked that when the two methods are applied to the same data sample, the results agree within the expected errors. The present method removes the need for geometrical acceptance calculations.

3. SELECTION OF CHARGED CURRENT (CC) EVENTS

The film was scanned twice for any neutrino or antineutrino interaction candidates inside the TST ("H" events). A separate scan and partial rescans of a small region in the neon directly downstream of the target, and therefore traversed by the same flux, was performed to find interactions in the neon mixture ("Ne" events). Losses of events were evident near the side walls of the TST and so correspondingly reduced fiducial volumes were used both in the hydrogen and in the neon. Within these volumes the events showed spatial distributions compatible with the known beam profiles. The overall scan efficiency was high for all final state topologies, except for antineutrino interactions giving only one charged track. For these the efficiency was very low. They have therefore been removed from the analysis and corrected for later.

The events were fully measured including all their possibly-associated neutral secondaries (γ -rays, vees and secondary neutron or K_L^0 interactions) observed in the hydrogen or the neon-hydrogen mixture. For this analysis however, only the possible γ -rays and vees pointing with good probability to the main vertex of the event were kept and all the possible secondary neutron or K_L^0 interactions were discarded.

After measurement the charged current events were selected by a kinematic method. This used the variable F which was calculated for each charged particle in each event and was defined as follows:

$$F = P_T' P_L' / P_T'' P_L''$$

where

P_T is the transverse momentum of the particle with respect to the beam direction,

P_T' is its transverse momentum with respect to the total momentum vector of all other particles,

P_L is its longitudinal momentum in the beam direction, and

P_T'' is the root-mean-square transverse momentum of all the other particles relative to their total momentum vector.

In each event, the particle having the largest value of F was chosen as the muon candidate. The definition of F reflects the main kinematic features of charged current, CC, interactions in that the muon generally has higher longitudinal and transverse momenta than any hadron and, because of the limited hadron transverse momentum relative to the hadron shower axis, P_T'' is usually smallest when the muon is correctly chosen. Similar variables to F have been used previously⁽⁶⁾. P_T'' carries no information in events consisting of two charged particles only. For these events P_T'' was set equal to one.

The event was classified as CC if its visible energy E_{vis} exceeded 10 GeV and the muon candidate had momentum p_μ above 5 GeV/c and had appropriate charge and left the bubble chamber without interaction. These cuts considerably reduce the contamination of the CC sample by other interactions. This contamination was further reduced by placing a cut on the azimuthal angle ϕ about the beam direction between the transverse momentum vectors of the muon candidate and of the hadron jet. In a genuine CC event with all particles in the final state detected, ϕ would be 180° . Energy losses reduce this. We required ϕ to exceed 60° .

The numbers of CC events found within the cuts are summarized in Table 1. The overall scanning efficiencies after a double scan in the hydrogen and a partial rescans in the neon are also given. The scanning efficiencies were found to depend on multiplicity. The figures given are weighted averages over the multiplicity distributions.

4A) CORRECTIONS TO TOTAL RATES

The corrections to the total rates are described below in detail for the neutrino H sample. They are collated, for all samples, in Table 2. The corresponding corrections to the ξ distributions are discussed later in Section 7.

Loss of CC events

The efficiency of the kinematic selection method was measured using a calibration sample of CC events selected by the EMI and having association

χ^2 values below 10 in both planes of the EMI. With this latter restriction the probability of calling a hadron a muon, determined from the rate of spurious like-sign dimuon events, was very low (0.2%).

Of the calibration sample of events passing the E_{vis} and p_μ cuts, (94.9 $\pm$ 0.9)% are also selected by the kinematic method and lie within the ϕ cut. Allowing for the small contamination of hadrons misidentified as muons in the calibration sample, the selection efficiency of the kinematic method is therefore (95.1 $\pm$ 0.9)%. The 4.9% of events not selected by the kinematic method includes 1.5% lost by the ϕ cut.

Events falsely selected as CC by the kinematic method

While 815 events were selected as CC by the kinematic method, a further 33 were inside the ϕ cut but were rejected since the best muon candidate interacted. These were largely neutral current interactions. The number of falsely selected events is therefore obtained by weighting the 33 events by the appropriate ratio of leaving to interacting tracks. From the CC sample after removing the muon tracks, this ratio was found to be 0.90 ± 0.15 . Therefore 30 $\pm$ 7 events, i.e. (3.6 $\pm$ 0.9)%, were falsely selected.

Events on neon in the H samples

There was a small contamination of neon inside the TST. Therefore events in the H sample with even prong number or with several baryons or with overall charge different from 1 were removed. Using the number of even prong events in the H sample and the ratio of even to odd multiplicities in the Ne sample, the expected number of odd multiplicity neon events in the H sample was calculated. This indicated that 20 $\pm$ 6 unidentified neon events remained in the neutrino H sample.

Loss due to the cut on E_{vis}

Due to energy loss via the escape of neutral particles, events are degraded in energy below the E_{vis} cut. Using a detailed Monte-Carlo simulation of such effects (Section 6), it was estimated that 0.7% of the

events with neutrino energy above 10 GeV and p_μ above 5 GeV/c were lost below the 10 GeV cut on E_{vis} .

4B) CORRECTIONS TO RATIOS OF TOTAL RATES

The remaining corrections were applied directly to the event-rate ratios between hydrogen and neon rather than to the individual data samples:

Correction for the effects of the $p_\mu > 5$ GeV/c cut

The events lost by this cut are predominantly high y events. Their removal affects the ratios only insofar as the y distributions on hydrogen and neon are different. The corrections depend only on the assumed proportion of scattering off the sea in neon and the assumed ratio of hydrogen to neon cross sections and are very small (1%) for all reasonable values of these parameters.

Correction for removal of single track events

No CC neutrino interactions on neutrons or protons give less than two charged secondaries. The neutrino samples thus need no correction. But in the antineutrino case the $\bar{\nu}p \rightarrow \mu^+ + \text{neutrals}$ channel was removed from both the H and Ne samples. To correct for this we used the result that (8.4 $\pm$ 0.4)% of CC events from $\bar{\nu}$ interactions on an isoscalar target have only one charged secondary⁽⁷⁾. This measurement was made with the same antineutrino beam and at the same time as the present experiment. The 8.4% single track events comprise half in the quasi-elastic channel and half in inelastic channels. Applying the 8.4% to the Ne sample, after making a small correction for non-isoscalarity of the target, implies a loss of (8.6 $\pm$ 0.4)% of the CC Ne events. The corresponding loss from the H sample, determined from the number of events lost in neon scaled by the relative numbers of protons in the hydrogen and neon fiducial volumes, is (13.3 $\pm$ 1.6)%. The corresponding correction to the ratio is (5 $\pm$ 1)%.

Allowance for the incomplete overlap of the H and Ne samples

The ratio of cross-sections on Ne and H can be determined in a completely beam independent way if the Ne and H data come from identical film samples. For the antineutrino data this was the case. But for the neutrino data, more film was scanned inside the TST than in the neon. The ratio therefore requires correction by the flux ratio between the two film samples. This was determined from the muon flux monitor detectors in the neutrino beam shielding to be 1.99 ± 0.02 . This is an average over several detectors and the quoted error is their spread.

5. TOTAL CROSS-SECTION RATIOS BETWEEN HYDROGEN AND ISOSCALAR TARGETS

Applying the above corrections and allowing for the appropriate ratios of fiducial volume lengths and densities, the ratios of the cross-section per nucleon on an isoscalar neon target (σ_I) to that on a proton (σ_p) are:

$$r_v = \frac{\sigma_{vI}}{\sigma_{vp}} = 1.44 \pm 0.09 \text{ statistical} \pm 0.02 \text{ systematic,}$$

$$r_{\bar{v}} = \frac{\sigma_{\bar{v}I}}{\sigma_{\bar{v}p}} = 0.81 \pm 0.07 \text{ statistical} \pm 0.01 \text{ systematic.}$$

where the systematic errors quoted arise from uncertainties in the flux ratios and liquid densities and in the correction for single track events.

Using $\frac{\sigma_{vI}}{E_v} = 0.66 \times 10^{-38} \text{ cm}^2/\text{GeV}$ and $\frac{\sigma_{\bar{v}I}}{E_v} = 0.29 \times 10^{-38} \text{ cm}^2/\text{GeV}$ obtained by interpolation between values from references 8 and 9, our measurements correspond to

$$\frac{\sigma_{vp}^-}{\sigma_{vp}} = 0.78 \pm 0.08,$$

$$\frac{\sigma_{vp}^-}{E_v} = (0.46 \pm 0.03) \times 10^{-38} \text{ cm}^2/\text{GeV};$$

$$\frac{\sigma_{\bar{v}p}^-}{E_v} = (0.36 \pm 0.03) \times 10^{-38} \text{ cm}^2/\text{GeV}$$

6. CORRECTION FOR ENERGY LOSS AND SMEARING

Energy is lost from the hadron jet by the escape of γ -rays and neutral hadrons from the chamber. We correct for this using the transverse momentum balance of the event:

$$\frac{P_L^H(\text{corrected})}{P_L^H(\text{observed})} = \frac{\begin{bmatrix} P_T^H \\ P_T^H \\ P_T^H \end{bmatrix}^{\text{observed}}}{\begin{bmatrix} P_T^H \\ P_T^H \\ P_T^H \end{bmatrix}^{\text{observed}}} = \begin{bmatrix} P_T^H \\ P_T^H \\ P_T^H \end{bmatrix}^{\text{observed}}_{\mu\nu}$$

where P_L^H and P_T^H refer to the momentum of the hadron shower parallel and transverse to the beam and $\mu\nu$ means in the muon-neutrino plane.

In the few cases where the angle between P_T^H and P_T^H is less than 90° this correction is unreliable. These events were instead given the mean correction of the sample. This mean correction to P_L^H was approximately 24% for all data samples.

The effects of energy loss and of the energy correction scheme were investigated by detailed Monte-Carlo simulation of the processes involved. Good agreement was obtained between the Monte-Carlo and the real events for the distributions of all relevant experimental quantities. Figure 1 illustrates this agreement for the neutrino samples for the components of the transverse momentum of the hadron jet in the $\mu\nu$ plane and normal to it. Both distributions are sensitive to the energy loss. The Monte-Carlo program provides both the correction for the E_{vis} cut (Table 2) and the smearing coefficients (Table 3) which were used to correct the experimental ξ distributions to allow for these effects.

7. THE ξ DISTRIBUTIONS

The corrected ξ distributions for events in H and Ne for both neutrino and antineutrino are shown in figure 2. To take account of the variation of scanning efficiency with event multiplicity, each event is included in the distributions with an appropriate weight. The corrections for contaminations and losses detailed in Section 4A have been applied in each

bin separately and the distributions adjusted with the smearing coefficients (Table 3) which take account of energy loss and the resolution of the energy correction method. Allowance for the p_μ cut is made later (see below) but the antineutrino ξ distributions have been corrected for the loss of single charged track events as follows. These derive equally (7) from elastic and inelastic interactions. Correction for the lost elastics is simple since their ξ distribution can be calculated from their form factor (10). This calculated distribution does not differ markedly from the distribution of the experimental sample, unlike the x distribution where all elastics are at $x = 1$. Since no Δ^0 was seen in the $\bar{\nu}p \rightarrow \mu^+\pi^-p$ events, the correction for the lost inelastics was made by appropriately scaling the experimental ξ distribution. The ξ distributions of the added one-prong events are shown in Figure 2.

8. EXTRACTION OF QUARK MOMENTUM FRACTION DISTRIBUTIONS FROM THE H DATA

With certain simplifying assumptions the valence quark distributions $U_V(\xi)$ and $D_V(\xi)$ and the overall level of the sea quark contribution may be extracted from the experimental ξ distributions. In the quark parton model, neglecting any charm quark contribution, the differential distributions of ν and $\bar{\nu}$ interactions on a proton may be written as

$$\frac{dN_p}{d\xi dy dE} = \frac{G^2 m E}{\pi} N_V^H \phi(E) [D_V + D_S + S + \bar{U}(1-y)^2]$$

$$\frac{dN_{\bar{p}}}{d\xi dy dE} = \frac{G^2 m E}{\pi} N_V^H \bar{\phi}(E) [(U_V + U_S)(1-y)^2 + \bar{D} + \bar{S}]$$

where $D(\xi)$ and $U(\xi)$ are quark momentum fraction distributions, the suffices ν and s refer to valence and sea quarks and $\bar{U}, \bar{D}$ and $\bar{S}$ are the similarly defined distributions for anti-quarks in the sea. $\phi(E)$ and $\bar{\phi}(E)$ are the computed shapes of the neutrino and antineutrino energy spectra while N_V^H and N_V^H are the integrated ν and $\bar{\nu}$ beam intensities averaged over the fiducial volume.

Assuming scale invariance, the quark momentum-fraction distributions depend only on ξ and the expressions integrate to give:

$$\frac{dN_p}{d\xi} = \frac{G^2 m}{\pi} N_V^H [I_1(D_V + D_S + S) + I_2\bar{U}]$$

$$\frac{dN_{\bar{p}}}{d\xi} = \frac{G^2 m}{\pi} N_V^H [I_3(U_V + U_S) + I_4(\bar{D} + \bar{S})]$$

where

$$I_1 = \int_{E_{\min}}^{E_{\max}} \int_0^Y E\phi(E) dy dE, \quad I_2 = \int_{E_{\min}}^{E_{\max}} \int_0^Y E\phi(E) (1-y)^2 dy dE$$

and I_4, I_3 are similarly defined for the antineutrino spectrum.

$E_{\min}$ is determined by the 10 GeV energy cut and $E_{\max}$ by the upper limit to the neutrino spectrum, effectively 200 GeV. $Y_{\max}$ at a given energy E is determined by the 5 GeV/c cut on the muon momentum. The integrated beam intensities N_V^H and N_V^H were constrained via our normalisation to interactions on neon by the measurements of the isoscalar cross-section ratio $\sigma_{\nu I}/\sigma_{\bar{\nu} I} = 2.25 \pm 0.16$ and geometric mean $(\sigma_{\nu I}\sigma_{\bar{\nu} I})^{1/2}/E_0 = (0.45 \pm 0.02) \times 10^{-38} \text{ cm}^2/\text{GeV}$. These values were obtained by interpolation from references 8 and 9.

The two experimental distributions are thus expressed in terms of 8 unknown quark functions. To reduce this we assume (11) that all sea quark distributions have the same shape and that $U_S = \bar{U} = D_S = \bar{D}$ and $S = \bar{S} = 0.27\bar{U}$. Parameterising the shapes of the momentum-fraction distributions by

$$U_V(\xi) = \frac{2\Gamma(\alpha + \beta + 1)}{\Gamma(\alpha)\Gamma(\beta + 1)} \xi^{\alpha-1} (1-\xi)^{\beta-1}$$

$$D_V(\xi) = \frac{\Gamma(\alpha + \beta + 1)}{\Gamma(\alpha)\Gamma(\beta + 1)} \xi^{\alpha-1} (1-\xi)^{\beta-1}$$

and

$$\bar{U}(\xi) = \delta(1 + \gamma)(1 - \xi)^{\gamma} \quad \text{with } \gamma = 4.55 \pm 0.49 \quad (12)$$

the best fit to the two H distributions gives the results shown in table 4 for fit 8.1. Fit 8.2 shows that the effective measurement of the cross section ratio, by the shape of the $d\sigma/d\xi$ distributions and the model, agrees well with the expected value.

Using the level of the sea thus estimated, a bin-by-bin extraction of D/U may be performed. The results are given in Figure 3a. In the simplest quark model, U_v and D_v have the same ξ dependence and $D_v/U_v = \frac{1}{2}$. More realistic models predict the ratio to fall with ξ . Feynman and Field⁽¹³⁾ predict the ratio falls to zero as $\xi \rightarrow 1$, Partar and Jackson⁽¹⁴⁾ predict it falls to 1/5, and models postulating scattering from diquarks⁽¹⁵⁾ predict it falls to 1/4. Our data clearly indicate a falling trend but cannot distinguish further between these various models.

Figures 3b and 3c compare our results for ξ above 0.2 where the sea is negligible with other bubble chamber results⁽¹⁶⁻¹⁹⁾ and with measurements using electron⁽²⁰⁾ and muon beams⁽²¹⁾. The various results obtained from bubble chambers with neutrino beams seem generally consistent. The large systematic errors in the muon scattering data⁽²¹⁾ preclude any more precise comparison with the SLAC data than can be done with the neutrino bubble chamber results. The slope of D/U seems to be smaller for all the bubble chamber data. However, including the SLAC n/p data (with x' greater than 0.2) gives the good overall fit 8.3 with somewhat larger values of α_d and β_d . The fitted curve is shown as the dot-dash line on figure 3c. Measurements of D/U extracted from heavy nuclei or from H_2-D_2 comparisons could suffer from nuclear effects as discussed in section 9.

9. COMPARISON OF H AND Ne ξ DISTRIBUTIONS

Assuming that charge symmetry relates the quark distributions in protons and neutrons, if neon were an equal mixture of unbound protons and neutrons, the ξ distributions for v and $\bar{v}$ interactions with neon would be given by:

$$\frac{d\eta_v}{d\xi} = \frac{G^2 m}{\pi} N_v^{Ne} \left[I_1 \frac{1}{2} (U_v + U_s + D_v + D_s + 2S) + I_2 \frac{1}{2} (\bar{U} + \bar{D}) \right]$$

$$\frac{d\eta_{\bar{v}}}{d\xi} = \frac{G^2 m}{\pi} N_v^{Ne} \left[I_3 \frac{1}{2} (U_v + U_s + D_v + D_s) + I_4 \frac{1}{2} (\bar{U} + \bar{D} + 2S) \right]$$

where the factors I_1 etc. have the same meaning as before. To allow for the slightly non-isoscalar Ne/H mixture used in the experiment the factors of $\frac{1}{2}$ in the equations were changed by approximately 2%. N_v^{Ne} and $N_{\bar{v}}^{Ne}$ are the integrated neutrino and antineutrino beam intensities averaged over the neon fiducial volume. These were again related by requiring the cross sections to have the values quoted in Section 8.

The equations neglect any effects due to the neutrons and protons being bound in a nucleus. Both theoretical calculations⁽²²⁾ and recent experimental evidence^(3,4,5) suggests that these effects are strongly ξ dependent. We have therefore searched for such effects by fitting all four ξ distributions simultaneously to the analytic forms for U_v , D_v and the sea given in Section 8 but including in each bin in ξ a free parameter C which is the ratio of the Ne data point to the prediction for it from the H data. After this fit 9.1, the parameters α_u , β_u , $\alpha_d - \alpha_u$, $\beta_d - \beta_u$ and δ show insignificant variation from the fit 8.1 to the H data alone whilst C shows no significant departure from unity across the entire ξ range (see figure 4 and table 5). Including the SLAC n/p data in this fit has a negligible effect on the points plotted on figure 4.

Measurements have recently been reported on the differential cross section ratio between iron and deuterium targets^(3,4) as a function of x . The EMC Collaboration found a linear dependence on x with a slope parameter given by $b = -0.52 \pm 0.21$, including both statistical and systematic errors. If, for comparison, we fit our data over the whole range in the same way we find $b = -0.07 \pm 0.26$, see table 4, fit 9.2. However if we only use our data with ξ above 0.1 then $b = -0.41 \pm 0.30$.

scattering from aluminium and deuterium also has a similar q^2 range to ours. The drop in the relative ν -Ne cross section below $\xi \sim 0.1$ indicated in figure 4 and table 5 presumably corresponds to the clear shadowing effects seen in the aluminium data. A curve representing the aluminium results fits our data well and reduces the χ^2 by 3, (table 4, fit 9.8). (On the other hand both our data and the electron scattering results seem in contradiction to the apparently higher slope, about -0.9, deduced from a comparison of carbon⁽²⁴⁾ and deuterium data from two experiments.)

We conclude that the apparent difference between our neutrino data and EMC for ξ below 0.1 is most probably real and due to shadowing effects. Our data agree better with the aluminium and deuterium results than with the total absence of nuclear effects, although the latter is not excluded. However it seems that in our data any ξ dependent nuclear correction factors are about the same size as the statistical errors, while the overall correction is small.

10. COMBINATION OF ALL FOUR DATA SETS

All four distributions may be combined to check for systematic effects which could derive from a q^2 dependence of the quark functions since the mean q^2 of the ν and $\bar{\nu}$ event samples is different, $\langle q^2 \rangle_\nu = 6.9$, $\langle q^2 \rangle_{\bar{\nu}} = 4.3 \text{ GeV}^2/c^2$. With the nuclear correction factors set to unity the distributions were refitted allowing β_u to be different for ν and $\bar{\nu}$ data. The fit reveals no significant difference between them.

Since all four data sets are consistent they have been combined to give the global fit 10.1 in table 4. The effective measurements of the cross section ratio by the model (as in fit 8.2) is shown as fit 10.2. The cross section ratio $(\sigma_\nu/\sigma_{\bar{\nu}}) = 2.28 \pm 0.12$ is determined as well as any measurements at these energies. Including the curve representing the nuclear effects observed in the aluminium to deuterium comparison⁽⁵⁾ has a negligible effect on the parameters, see fit 9.8.

In the absence of nuclear effects the cross-section ratios for interactions on neutrons and protons follow directly from the isoscalar to proton ratios since $\sigma_I = (\sigma_n + \sigma_p)/2$:

In principle the effects in neutrino and muon scattering may differ because of the different couplings of $W^\pm$ and photons. They can therefore be compared only via a model. Jaffe⁽²³⁾ interprets the EMC effect as the sum of two distinct effects, namely a shrinkage of the valence quark distribution and a rise in the level of the sea, occurring in heavy nuclei as compared with hydrogen or deuterium. Other authors offer similar parameterisations but differing explanations of one or both effects. We therefore compare in this spirit.

Starting from the best fit values in the previous section, we find that the EMC line for muon scattering corresponds well to β_d and β_u being 0.22 bigger in iron than in hydrogen or deuterium and the sea contribution, δ , a factor 1.4 larger, all other parameters remaining unchanged. The best fit to our data, now including both sets of Ne data and two additional parameters, $(\beta_{Ne} - \beta_H)$ and (δ_{Ne}/δ_H) , to describe the nuclear effects in neon, gives the results shown in table 4, fit 9.3. It can be seen that $(\beta_{Ne} - \beta_H)$ is consistent with zero and (δ_{Ne}/δ_H) with 1, while there is no appreciable movement of any other parameters. Setting $(\beta_{Ne} - \beta_H)$ to 0.22 gives fit 9.4, while setting (δ_{Ne}/δ_H) to 1.4 gives fit 9.5. This extra sea in the neon forces an overall χ^2 increase of 5. Setting both $(\beta_{Ne} - \beta_H)$ to 0.22 and (δ_{Ne}/δ_H) to 1.4 also increases χ^2 by 5, fit 9.6. These may be combined into one parameter, $F_J = (\beta_{Ne} - \beta_H)/0.22 = (\delta_{Ne}/\delta_H - 1)/0.4$ which represents the fraction of the total Jaffe effect seen in our data. We find F_J to be $(-4 \pm 40)\%$, see table 4, fit 9.7.

Thus our data give no indication of any low- x excess and are over two standard deviations away from the central value quoted by EMC. The total errors quoted by the two experiments are similar and rather large, so they are not in disagreement. However the typical q^2 value in our data for $x \sim 0.1$ is 4 GeV^2 and for x below 0.05 only 1.5 GeV^2 , much smaller than in the EMC data. Furthermore the neon nucleus is both smaller and has less binding energy per nucleon than iron. Thus the difference may well be real.

Since the atomic number of neon (10) is close to that for aluminium (13), one may expect nuclear effects in our data to be similar to those recently reported by Bodek et al⁽⁵⁾. Their comparison of electron

$$\begin{aligned}(\sigma_n/\sigma_p)_{\nu} &= R_{\nu} = 1.88 \pm 0.18(\text{stat}) \pm 0.04(\text{syst}), \\ (\sigma_n/\sigma_p)_{\bar{\nu}} &= R_{\bar{\nu}} = 0.62 \pm 0.14(\text{stat}) \pm 0.02(\text{syst}).\end{aligned}$$

However the nuclear effects can be modelled by including a parameter C_{tot} which gives the overall ratio of the Ne to the prediction from the H data. We find $C_{\text{tot}} = \text{Ne}/\text{H} = 1.00 \pm 0.04$. Including C_{tot} we measure

$$\begin{aligned}R_{\nu} &= 1.88 \pm 0.19(\text{stat}) \pm 0.04(\text{syst}) \\ R_{\bar{\nu}} &= 0.62 \pm 0.14(\text{stat}) \pm 0.02(\text{syst})\end{aligned}$$

The BEBC deuterium experiment using a similar beam measures R_{ν}^{well} , $R_{\nu}^{\text{well}} = 0.51 \pm 0.03(19)$. The deuterium measurements of R_{ν}^{well} agree with ours but their precision is limited to ± 0.25 by the poorly known rescattering correction.

11. SUMMARY AND CONCLUSIONS

The results of this track sensitive target experiment have inherently small systematic errors. Charged current interactions in hydrogen and neon volumes traversed by the same neutrinos and antineutrinos are compared directly. Neutral secondaries from the hydrogen interactions are detected and measured as efficiently as those from neon interactions usually are. Thus the unsmearing corrections and their inherently large systematic uncertainties, which are throughout included in the final errors, do not dominate the final errors.

The ratios of the cross section per nucleon on an isoscalar neon target (σ_I) to that on a free proton (σ_p) were measured to be

$$\frac{\sigma_{\nu I}}{\sigma_{\nu p}} = 1.44 \pm 0.09$$

$$\frac{\sigma_{\bar{\nu} I}}{\sigma_{\bar{\nu} p}} = 0.81 \pm 0.07$$

Using $\sigma_{\nu I}/E = 0.66 \times 10^{-38} \text{ cm}^2/\text{GeV}$ and $\sigma_{\bar{\nu} I}/E = 0.29 \times 10^{-38} \text{ cm}^2/\text{GeV}$, these measurements correspond to

$$\frac{\sigma_{\nu p}}{E} = (0.46 \pm 0.03) \times 10^{-38} \text{ cm}^2/\text{GeV}$$

$$\frac{\sigma_{\bar{\nu} p}}{E} = (0.36 \pm 0.03) \times 10^{-38} \text{ cm}^2/\text{GeV}$$

$$\frac{\sigma_{\nu p}^-}{\sigma_{\nu p}} = 0.78 \pm 0.08$$

Parameters describing the shapes of the quark and antiquark ξ distributions were fitted to the hydrogen data alone, normalised via the measured values of $\sigma_{\nu I}/\sigma$ and $\sigma_{\bar{\nu} I}/\sigma_{\nu p}$ to external information regarding the values of $\sigma_{\nu I}$ and $\sigma_{\bar{\nu} I}$. For the form of parameterisation specified in section 8, the result (fit 8.1) is

$$\alpha_u = 0.53 \pm 0.09$$

$$\beta_u = 2.85 \pm 0.33$$

$$\alpha_d - \alpha_u = 0.10 \pm 0.11$$

$$\beta_d - \beta_u = 1.05 \pm 0.42$$

$$\delta = 0.023 \pm 0.004$$

This parameterisation fits the data well (fig. 2).

Using these values, the forms and normalisations of the νNe and $\bar{\nu}\text{Ne}$ ξ distributions can be predicted assuming that nuclear effects are absent.

Comparison of the actual neon data with these predictions (fig. 4 and table 5) give a direct measurement of these nuclear effects. Various parameterisations of such effects have also been compared with the data. The best fit was given by a curve representing the SLAC A2/D2 data of Bodek et al(5) in a similar q^2 range. Assuming no nuclear effects worsened χ^2 by 3, corresponding to a 1.7 σ effect, and assuming the central value found by the EMC collaboration at higher q^2 in a heavier target worsened χ^2 by 9, corresponding to a 3 σ effect. Thus the difference between our data and the EMC data is probably real and due to shadowing of the kind clearly indicated by the SLAC data.

Our previous analysis⁽²⁾, which compared νH and νNe interactions to extract σ_n/σ_p and quark distribution functions, made the then-standard assumption that nuclear effects were negligibly small. Finally we have therefore repeated this analysis using our present data. We find that indeed the nuclear effects observed in our data are negligibly small (compare, for example, fits 9.8 and 10.1 in table 4). The σ_n/σ_p values extracted are

$$(\sigma_n/\sigma_p)_\nu = 1.88 \pm 0.19$$

$$(\sigma_n/\sigma_p)_\mu = 0.62 \pm 0.14$$

ACKNOWLEDGEMENTS

We wish to thank the teams at CERN who built the TST and operated BEBC for their excellent results. We also appreciate the careful attention the film received from our scanning and measuring teams.

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TABLE CAPTIONS

Table 1 : The events used for the cross section measurements.

Table 2 : The corrections to the event samples for the various losses and backgrounds.

Table 3 : The corrections to the ξ distributions due to the imprecise energy estimate of the hadron showers.

Table 4 : The results of the fits to the ξ distributions. The first error is statistical and the second systematic. The systematic errors correspond to $\pm 30\%$ of the amounts by which the parameters moved when the smearing corrections shown in table 3 were applied. For all fits the cross sections and γ were constrained to the measurements quoted in section 8, unless new values are given. The γ indicates which data were included in the fit.

Table 5 : The values of C, the ratio of the neon data to the prediction derived from the fits to the hydrogen data, and typical q^2 values. The errors are as detailed for table 4.

Table 1

Sample	Fiducial Volume	No. of CC Events	Scan Efficiency %
νH	$1.8m^3$	813	97.1 ± 0.4
νNe	$0.22m^3$	838	97.0 ± 1.2
$\bar{\nu} H$	$1.8m^3$	301	96.3 ± 0.7
$\bar{\nu} Ne$	$0.37m^3$	614	98.2 ± 1.0

Table 2

Sample	Loss of CC Events	False cc Correction	Neon Contamination	Loss due to E_{vis} Cut	Relative Effect of P_{μ} Cut	Loss of Single Track Events
νH	$+(4.9 \pm 0.9)\%$	$-(3.6 \pm 0.9)\%$	$-(2.5 \pm 0.7)\%$	$+(0.7 \pm 0.1)\%$	-	0
νNe	$+(6.5 \pm 1.1)\%$	$-(3.3 \pm 1.0)\%$	0	$+(1.8 \pm 0.1)\%$	$+(0.3 \pm 0.1)\%$	0
$\bar{\nu} H$	$+(3.7 \pm 1.1)\%$	$-(5.7 \pm 2.7)\%$	$-(1.7 \pm 1.5)\%$	$+(0.8 \pm 0.1)\%$	-	$+(13.3 \pm 0.6)\%$
$\bar{\nu} Ne$	$+(5.7 \pm 1.1)\%$	$-(4.8 \pm 1.8)\%$	0	$+(1.9 \pm 0.1)\%$	$+(0.8 \pm 0.3)\%$	$+(8.6 \pm 0.4)\%$

Table 3

ξ	0 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.6	> 0.6
νH	1.00	1.01	1.05	1.02	0.98	0.77
$\bar{\nu} H$	1.00	1.03	1.05	1.07	0.93	0.74
νNe	1.09	1.09	1.12	1.10	1.00	0.53
$\bar{\nu} Ne$	1.09	1.17	1.14	1.11	0.92	0.46

Table 4

Fit	$\frac{d\sigma}{d\xi}_H$	$\frac{d\sigma}{d\xi}_{Ne}$	SLAC n/p	α_u	$\alpha_d - \alpha_u$	β_u	$\beta_d - \beta_u$	1000 δ	χ^2	NDF	Comments or other parameters
8.1	✓			$0.53 \pm 0.09 \pm 0.02$	$0.10 \pm 0.11 \pm 0.00$	$2.85 \pm 0.31 \pm 0.11$	$1.05 \pm 0.42 \pm 0.00$	$23 \pm 4 \pm 0$	7.1	11	H only, dashed line on fig 3
8.2	✓			$0.50 \pm 0.11 \pm 0.02$	$0.15 \pm 0.16 \pm 0.00$	$2.79 \pm 0.34 \pm 0.11$	$1.15 \pm 0.49 \pm 0.00$	$24 \pm 4 \pm 0$	7.0	10	$(\sigma_v/\sigma_v^-) = 2.40 \pm 0.35 \pm 0.00$
8.3	✓		✓	$0.53 \pm 0.05 \pm 0.02$	$0.14 \pm 0.03 \pm 0.00$	$2.73 \pm 0.20 \pm 0.10$	$1.56 \pm 0.09 \pm 0.01$	$22 \pm 4 \pm 0$	32.2	49	dot-dashed line on fig 3c
9.1	✓	✓		$0.53 \pm 0.08 \pm 0.02$	$0.10 \pm 0.09 \pm 0.00$	$2.88 \pm 0.28 \pm 0.10$	$1.05 \pm 0.40 \pm 0.00$	$22 \pm 4 \pm 0$	11.6	19	Ne/H ratios as $f(\xi)$. See fig 4 and table 5.
9.2	✓	✓		$0.59 \pm 0.06 \pm 0.05$	$0.08 \pm 0.09 \pm 0.02$	$3.12 \pm 0.21 \pm 0.23$	$0.97 \pm 0.41 \pm 0.10$	$21 \pm 3 \pm 1$	19.8	25	$b = -0.07 \pm 0.24 \pm 0.11$
9.3	✓	✓		$0.60 \pm 0.06 \pm 0.05$	$0.06 \pm 0.09 \pm 0.02$	$3.11 \pm 0.23 \pm 0.21$	$0.95 \pm 0.40 \pm 0.10$	$22 \pm 4 \pm 1$	19.5	25	$(\beta_{Ne} - \beta_H) = 0.06 \pm 0.14 \pm 0.02$ and $(\delta_{Ne}/\delta_H) = 0.95 \pm 0.16 \pm 0.03$
9.4	✓	✓		$0.60 \pm 0.06 \pm 0.04$	$0.06 \pm 0.09 \pm 0.01$	$2.99 \pm 0.19 \pm 0.21$	$1.01 \pm 0.38 \pm 0.07$	$21 \pm 4 \pm 1$	20.8	26	$(\delta_{Ne}/\delta_H) = 0.98 \pm 0.16 \pm 0.02$ $(\beta_{Ne} - \beta_H)$ fixed to 0.22
9.5	✓	✓		$0.58 \pm 0.06 \pm 0.05$	$0.11 \pm 0.09 \pm 0.03$	$3.02 \pm 0.22 \pm 0.22$	$1.14 \pm 0.38 \pm 0.12$	$15 \pm 3 \pm 0$	24.6	26	$(\beta_{Ne} - \beta_H) = 0.12 \pm 0.14 \pm 0.07$ (δ_{Ne}/δ_H) fixed to 1.4
9.6	✓	✓		$0.58 \pm 0.06 \pm 0.04$	$0.10 \pm 0.08 \pm 0.01$	$2.95 \pm 0.18 \pm 0.22$	$1.17 \pm 0.37 \pm 0.10$	$16 \pm 3 \pm 0$	25.2	25	$(\beta_{Ne} - \beta_H)$ fixed to 0.22 and (δ_{Ne}/δ_H) fixed to 1.4
9.7	✓	✓		$0.59 \pm 0.06 \pm 0.04$	$0.07 \pm 0.09 \pm 0.02$	$3.16 \pm 0.22 \pm 0.23$	$0.94 \pm 0.41 \pm 0.09$	$21 \pm 4 \pm 1$	19.8	26	$F_J = -0.04 \pm 0.38 \pm 0.13$
9.8	✓	✓		$0.58 \pm 0.06 \pm 0.04$	$0.07 \pm 0.09 \pm 0.02$	$3.09 \pm 0.18 \pm 0.26$	$0.94 \pm 0.38 \pm 0.12$	$21 \pm 3 \pm 0$	16.4	27	Al/D shape from ref 5 included
10.1	✓	✓		$0.59 \pm 0.06 \pm 0.04$	$0.08 \pm 0.09 \pm 0.02$	$3.16 \pm 0.19 \pm 0.26$	$0.94 \pm 0.39 \pm 0.12$	$21 \pm 3 \pm 1$	19.8	27	H+Ne, fit on fig 2
10.2	✓	✓		$0.59 \pm 0.06 \pm 0.04$	$0.08 \pm 0.09 \pm 0.02$	$3.15 \pm 0.19 \pm 0.26$	$0.97 \pm 0.40 \pm 0.12$	$21 \pm 3 \pm 0$	19.7	26	$(\sigma_v/\sigma_v^-) = 2.28 \pm 0.12 \pm 0.01$

Table 5

ξ	0 - 0.05	0.05 - 0.1	0.1 - 0.15	0.15 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.6	0.6 - 1
C	$0.92 \pm 0.12 \pm 0.01$	$0.89 \pm 0.09 \pm 0.00$	$1.13 \pm 0.09 \pm 0.01$	$1.07 \pm 0.09 \pm 0.01$	$1.04 \pm 0.08 \pm 0.03$	$1.11 \pm 0.09 \pm 0.01$	$0.91 \pm 0.08 \pm 0.01$	$0.91 \pm 0.14 \pm 0.16$
$\sim q_\nu^2$	1.8	4	6	7	9	11	12	12
$\sim q_\nu^2$	1.2	3	3	5	5	7	7	9

Figure Captions

Fig. 1 Comparison of Monte Carlo predictions (dashed lines) and data distributions for the component of the hadron momentum vector perpendicular to the muon neutrino plane, p_T^{out} , and in the plane in p_T^{in} .

Fig. 2 Measured $d\sigma/d\xi$ averaged over the beam spectrum in units of $20^2 \text{mb}/\pi$. Systematic errors are included. The full curve is the fit described in section 10. The dashed curve shows the one prong correction discussed in section 7.

Fig. 3a The variation of the ratio D/U with ξ . • Measured ratio before allowing for the sea contribution, with systematic errors included. o D/U after allowing for sea antiquarks. x D/U , allowing for sea quarks and antiquarks. -- Fit 8.1 to D_v/U_v described in section 8.

Fig. 3b Comparison with other bubble chamber measurements of D/U for $x > 0.2$.

Fig. 3c Comparison of D_v/U_v fit with electron and muon scattering experiments for $x > 0.2$, (with systematic errors included). -- fit 8.1, --- fit 8.3 including SLAC data.

Fig. 4 Measured variation of C , the ratio of the neon data to the prediction derived from the fits to the hydrogen data. Systematic errors are included.

FIGURE. 1

FIGURE 2

FIGURE 3

FIGURE 4