A STUDY OF THE EMC EFFECT USING NEUTRINO AND ANTINEUTRINO
INTERACTIONS IN NEON AND DEUTERIUM

WA25 and WA59 Collaborations

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Abstract

Nearly 40,000 neutrino and antineutrino interactions in BEBC are compared to measure the differences between neon and deuterium in the quark and antiquark distributions and in the nucleon structure functions. The ratio of Ne to D cross sections indicates some decrease between $x \sim 0.2$ and $x \sim 0.6$. The y distributions show there is no significant increase in the neon sea, but prefer a small decrease. Taken altogether the x and y distributions and the measured total cross-sections indicate some change in the shape of the valence distributions. No significant dependence on A is observed for either the shape of the sea or the ratio of longitudinal to transverse cross-sections.

1. Introduction

The European Muon Collaboration observed that the differential cross sections per nucleon in inelastic lepton scattering vary with atomic number^[1]. This implied that the quark momentum distributions and, correspondingly, one or more of the nucleon structure functions, must vary. Subsequently there have been precision measurements using electron beams for values of the scaling variable x above 0.1^[2], while further data are available for muon scattering^[3]. Neutrino scattering data^[4-8], though often less precise, provide information for small values of x and for all values of y . Their particular merit is that they allow the behaviours of the quarks and antiquarks to be separated experimentally.

In this paper, the final statistics from the Big European Bubble Chamber (BEBC) on the comparison of neutrino and antineutrino scattering on deuterium and neon are presented. The analysis uses nearly 40,000 events. These are evenly divided between the two targets. The statistics are therefore effectively greater than in other neutrino experiments. The systematic errors are carefully controlled and are generally considerably smaller than the statistical errors. In particular there are no differences in acceptance between the two targets. The results given are therefore the most complete and precise results at present available using neutrino and antineutrino beams.

A previous publication^[5] included less than half the present antineutrino deuterium statistics. Only preliminary analyses of the neutrino data have been presented^[9].

2. Experimental Technique

The data come from exposures of BEBC to the CERN-SPS wide band neutrino and antineutrino beams produced by 400 GeV protons. The chamber was filled with deuterium, for experiment WA25, and with a 75 mole per cent neon-hydrogen mixture, for experiment WA59. The targets occupy the same volume and have identical spatial relationships to the beam and detectors. Beam conditions were carefully controlled throughout. Furthermore all the neutrino data, all the antineutrino neon data, and half the antineutrino deuterium data were taken consecutively during a relatively short period of some three months in 1980.

The data were entirely re-analysed for the present comparison. Identical data reduction and correction procedures were used. With the minor exceptions detailed below, data were only accepted from beam pulses with standard beam conditions and muon monitoring results. As a consequence, systematic errors were eliminated or minimised. Furthermore, possible biases in the shapes of differential distributions largely cancel in their ratios.

In particular:

- (a) Events were required to lie within the overlap of the target volumes used for event measurement by the two experiments. This ensures the same neutrino beam acceptance and the same acceptance for identifying secondary muons.
- (b) In general identical beam conditions were required⁺. For every beam pulse, the beam constancy was monitored with a stable precisely-calibrated array of muon flux detectors in the shielding^[10]. The data were rejected if the shape of the muon flux distribution was non-standard.
- (c) Charged Current (CC) events were identified using the same two-plane External Muon Identifier^[11]. The performance of each wire of the EMI

⁺ There were two exceptions. For half of the antineutrino deuterium data the beam alignment was slightly different, so it was not in fact possible to ensure that beam conditions were precisely identical; for these data it was also impractical to ensure that the muon identification conditions were identical. However any significant differences would also show up as differences in the energy or muon-momentum distributions of the events, compared with the other half of the antineutrino deuterium data. Such differences were searched for, none were detected. Furthermore, weighting the events to force the distributions to be identical had no significant effect on the results presented below. These data were therefore included even though strict application of our criteria would have excluded them (they were excluded for this reason, from a previous publication^[5], and no specific correction was considered necessary). The second exception, the absence of a beam stopper in the neutrino-deuterium run was the subject of a specific correction (see later).

was monitored during data taking using cosmic rays. Muons from neutrino interactions were required to hit the two EMI planes in coincidence. To ensure high detection efficiencies and low background, muons were required to have momenta over 5 GeV/c.

- (d) Only charged secondary particles (and associated Λ^0 and K_s^0 decays) were used in the selection of events and the determination of the kinematic variables. This minimises systematic errors due to different detection efficiencies in the deuterium and neon for other neutrals (gamma rays, neutrons and K^0 interactions).
- (e) The same event selection, method of energy correction, and analysis and fitting programs were used for neon and deuterium.

The missing hadronic energy in each event, taken away by missing neutrals, was corrected for using the relations:

$$E_v = p_\mu^L + C p_H^L \quad \text{where } C = \langle p_\mu^T \rangle / \langle p_H^T \rangle_{\mu\nu} \quad (1)$$

Here μ and H refer to the muon and the measured hadron shower, L and T to the longitudinal and transverse momentum components relative to the beam direction, $\mu\nu$ to the plane containing the neutrino and muon, and the expectation values to the total sample of events. The experimental values of C are shown in Table 1. The small differences between them may be understood in terms of (i) larger losses of final state neutrons in antineutrino than in neutrino data, (ii) the undetected neon fragments taking some final state momentum, and (iii) the presence in the neon data of some secondary tracks with close interactions, for which only a lower estimate of momentum is available.

The effects of 'smearing' on all distributions, due to the failure to reconstruct the complete hadron shower precisely for each event, were studied using a detailed Monte Carlo simulation of all the experimental conditions. In general the neon to deuterium ratio of the distributions was measured. Most systematic errors cancel in this ratio. In particular it was found that the relative smearing for neon and deuterium was small for x below 0.6. Therefore no Monte Carlo unsmearing corrections were applied.

The residual systematic errors on the neon to deuterium ratio, attributable to the choice of energy correction, were estimated from the data by using several different energy correction algorithms and, for each one, fitting a smooth curve to the measured ratio of distributions. The spread between the fitted curves was taken as the systematic error.

Corrections were applied for:

(a) **The scan efficiencies for the different data sets:**

These were corrected separately for each multiplicity, since the lower multiplicity events are more easily missed by the scanners. The efficiencies (see Table 1) were obtained by extra scans on the film after two main scans had been used to select the events for measurement. However, antineutrino interactions with only a positive muon and no other charged secondaries are found with low and badly determined efficiencies by simple scans of the film. In order to avoid larger corrections for such events they were removed from the antineutrino data. Only a residual ($-2 \pm 2\%$) correction to the antineutrino neon data for multiplicity changing reinteractions was then required.

(b) **Small differences in the neutrino beam running conditions:**

The neutrino-deuterium data were taken without a beam stopper after the target absorbing high energy secondaries at very small angles. The effects of removing the stopper ($+1 \pm 1\%$ overall) were calculated as a function of neutrino energy and appropriate corrections applied. All data were restricted to the beam energy region (15 to 160 GeV) where the expected differences between the neutrino flux for neon and deuterium were small.

(c) **The small background from neutral current (NC) events wrongly identified as CC events:**

This is different in the two liquids (i) because secondary particles interact more often in neon, and (ii) because the probability of an accidental coincidence between a leaving track and background hits in the EMI depends on the extracted proton beam intensity.

(d) **The reconstruction efficiencies for the deuterium data sets:**

Deuterium events that were not fully reconstructed (even after several

measurement passes) had been rejected. A multiplicity dependent weight accounted for this loss (the mean value is shown in Table 1). A different strategy had been applied when measuring the neon data so as to make all the neon events available.

3. Results

The raw numbers of events and the corrections to them are given in Table 1. Using the muon fluxes measured in the shielding, the target densities and a small correction for the non-isoscalarity of the neon-hydrogen mixture, we obtain the total cross section ratios shown in the same table.

The magnitudes of the total cross sections are well known to correspond to quarks and gluons carrying almost equal momentum fractions. The near equality of these total cross sections, in particular of the neutrino cross sections, therefore indicates that, within $\sim 4\%$, the integral gluon momentum fraction as well as the integral quark momentum fraction is the same in neon as in deuterium. On the other hand the gluon density per bound nucleon in iron, obtained by comparing cross-sections for inclusive muoproduction of J/ψ , has been reported^[12] to be 1.45 ± 0.25 times larger than in hydrogen or deuterium, at $x \sim 0.05$ and $Q^2 \sim M_\psi^2$.

The ratios of various differential distributions are shown in Figs 1-5 and Tables 2 and 3. All the figures show the statistical and systematic errors combined in quadrature. The curves shown on the figures refer to fits discussed later.

The ratio of the distributions of the muon variables p_μ^T and $v_\mu = (E_\mu - p_\mu^L)/M_{\text{proton}} \approx xy$ are shown in Fig 1 and Table 2. The virtue of these variables is that the muons are well measured and any residual differences in the reconstruction of the hadron showers do not affect these variables directly. Changes in x and y distributions would affect these distributions too, but might be difficult to disentangle.

More directly, the ratios of the x and y distributions themselves, for all Q^2 , for Q^2 above 1 GeV^2 and for Q^2 above 4.5 GeV^2 , are shown in Figs 2-4 and Table 3. The values obtained for x greater than 0.6, shown dashed in the figures, are considered unreliable because the smearing corrections to the neon and deuterium data sets separately are large (less than half the data

with measured x greater than 0.6 originated in the same x region). The data in this region are therefore excluded throughout the rest of this analysis.

Figures 2-4 show not only the ratios of the neutrino and antineutrino data separately but also the ratio of the combination of neutrino and antineutrino data, labelled $\nu + (\sigma_{\bar{\nu}}/\sigma_{\nu})\bar{\nu}$; in this combination the parity violating xF_3 term cancels. It may therefore be compared directly with electron and muon scattering data. Comparisons with similar published data^[2,3] are shown: there is good agreement.

There is no indication in Figs 2-4 of any dependence on Q^2 . However, Fig 5 which shows the ratio of the Q^2 distributions for three ranges of x , shows evidence of a shadowing effect for x below 0.15 and Q^2 below 0.5 GeV². This first observation of shadowing effects in neutrino scattering is to be discussed in more detail elsewhere^[13]. The result from Fig 5 that is important for the present analysis is that there is no indication of a dependence on Q^2 for Q^2 values exceeding 1 GeV². This paper therefore concentrates on the data with Q^2 above 1 GeV², excluding the region which may be affected by shadowing.

All electron and muon scattering data agree that the cross section ratio between heavy targets and deuterium decreases as x increases from 0.2 to 0.6. Examples are shown at the bottom of Figs 3 and 4, it can also be seen that our data indicate the same effect: a straight line fitted to our ten data points in Fig 3 with $0.2 < x < 0.6$ has a slope of -0.33 ± 0.18 .

The first muon scattering data, from the EMC collaboration^[1], suggested that this linear dependence on x continues to small x , so that the cross section ratio rises as x decreases from 0.2 to 0.0. This rise at small x has not, however, been seen in other data. The rise at small x reported by EMC was subsequently interpreted^[14] as due to a rise in the level of the $q\bar{q}$ sea in heavy nuclei. In neutrino and antineutrino scattering, such a rise would affect the ratios of the y distributions: these would fall a little with rising y for neutrino interactions and rise substantially with rising y for antineutrino interactions. Our data (Fig 3) tend to show the opposite effect. Straight lines fitted to the y distribution ratios in Fig 3 have slopes of 0.15 ± 0.09 for neutrino and -0.17 ± 0.08 for antineutrino.

It has been proposed^[15] that the value of $R = \sigma_L/\sigma_T$ is significantly larger in heavy nuclei. This was introduced to explain the failure of the SLAC data and of antineutrino data to confirm the small- x EMC effect. An increase in R in neon would tend to make the ratio of y distributions fall with increasing y for both neutrino and antineutrino scattering. It would therefore tend to cancel the effect of a rise in the $q\bar{q}$ sea in antineutrino scattering, but at the cost of adding to its effect in neutrino scattering. It will be shown that our neutrino data exclude this possibility (Section 4.2.2). More simply, for the parity conserving combination of neutrino and antineutrino data (shown at the bottom of Fig 3) changes in the level of the sea would have no effect: the deviation from unity in the ratio of y distributions shown therefore measures the change in R . No such deviation is observed. A straight line fitted to these data has a slope 0.06 ± 0.08 . A positive slope corresponds to R being smaller in neon, not larger.

This qualitative discussion illustrates that a complete and precise comparison of both neutrino and antineutrino data between different targets provides complete information on the differences in quark and antiquark momentum distributions and in structure functions between the targets. We now proceed to a more quantitative discussion.

4. Quantitative Comparison of Quark and Antiquark Momentum Distributions and Nucleon Structure Functions

4.1 Method of Comparison

The inclusive differential cross sections per nucleon for neutrino and antineutrino charged current scattering off an isoscalar target are given by:

$$\frac{d^2\sigma}{dx dy} = \frac{Q^2 ME}{\pi} \left[2xF_1 \left(1-y + \frac{y^2}{2} \right) + (F_2 - 2xF_1)(1-y) \pm xF_3 \left(y - \frac{y^2}{2} \right) \right] \quad (2)$$

where the $+(-)$ sign refers to neutrino (antineutrino) scattering and the nucleon structure functions $2xF_1$, F_2 and xF_3 depend on x and Q^2 . In terms of the quark and antiquark momentum distribution functions q and $\bar{q}$, which also depend on x and Q^2 , or equivalently in terms of the valence and sea quark momentum distribution functions q_v and q_s , one may write:

$$\begin{aligned}
2xF_1 &= q + \bar{q} = q_v + q_s \\
xF_3 &= q - \bar{q} = q_v \\
F_2 - 2xF_1 &= (q + \bar{q})R = (q_v + q_s)R \\
R &= \sigma_L / \sigma_T
\end{aligned} \tag{3}$$

Equation 2 then becomes:

$$\frac{d^2\sigma}{dx dy} = \frac{G^2 ME}{\pi} [(q_v + q_s)(1-y + \frac{y^2}{2} + (1-y)R) \pm q_v (y - \frac{y^2}{2})] \tag{4}$$

The x , y and Q^2 dependence of inclusive electron and muon scattering is given by similar expressions but the xF_3 term in Eq (2), and the corresponding term isolating q_v in Eq (4), are absent. This makes it impossible to separate valence and sea quark behaviours using inclusive electron and muon scattering data only. An important advantage of neutrino and antineutrino data is the fact that valence and sea quark behaviours are easily separated.

To use our data to compare the quark momentum distributions, and hence the structure functions, in neon and deuterium, the valence and sea quark momentum distributions q_v and q_s were first parametrised as:

$$\begin{aligned}
q_v &= \frac{3x^\alpha(1-x)^\beta}{\int x^{\alpha-1}(1-x)^\beta dx} \\
q_s &= S(1+\gamma)(1-x)^\gamma
\end{aligned} \tag{5}$$

and various parametrisations were used for R (see below). The differences $d\alpha = \alpha_{Ne} - \alpha_D$, $d\beta = \beta_{Ne} - \beta_D$, $d\gamma = \gamma_{Ne} - \gamma_D$, and the ratios $f_s = S_{Ne}/S_D$, $f_R = R_{Ne}/R_D$ between the parameter values for neon and deuterium were then determined from the data by fitting them to the observed ratios between the neon and deuterium data sets.

Previous analyses^[5,14] have effectively interpreted the data in terms of $d\beta$ and f_s . Here $d\alpha$ is introduced since it can be constrained by measuring the ratio of the total cross sections (see below). $d\gamma$ is introduced to investigate the sensitivity of the parameters to a change in the shape of the sea distribution. The ratio, f_R , is introduced to test the hypothesis^[15] that a variation of R with atomic number hampers the interpretation of the EMC effect in terms of $d\alpha$, $d\beta$ and f_s . The parameter $d\alpha/d\beta$ is used in the fits below since $d\alpha$ and $d\beta$ turn out to be highly correlated.

Various sets of parameter values^[4,16] were tried as the base parametrisation of q_v and q_s . The results obtained did not depend on which base parametrisation was used. In principle, kinematic corrections at low Q^2 of order $Q^2/\nu^2 = 4M^2 x^2/Q^2$ ('target mass' corrections etc), and others at higher Q^2 due to charm threshold effects, should have been included in Eq (3). However, these are fairly small effects, like the changes in the base parametrisation of q_v and q_s , that cancel in the neon to deuterium ratios and we considered them to be negligible.

4.2 Results of the Fits

The fit results are shown in Table 4. The overall Fit T gives the result of allowing all parameters ($d\alpha$, $d\alpha/d\beta$, $d\gamma$, f_s , f_R) to vary simultaneously when fitting to all three elements of our data, ie to the ratios of the x distributions, y distributions and total cross sections, simultaneously.

The other fits in Table 4, discussed in Sections 4.2.1 to 4.2.5 give the results of either: (i) fitting subsets of the available data elements, fixing any parameters that are then too poorly determined, in order to clarify which elements constrain which parameters; or (ii) fixing some parameters to particular values to test particular scenarios and elucidate the correlations between the fitted variables.

The ratios of the neutrino and antineutrino data sets were fitted simultaneously. For fits using two dimensional information (eg x and y), it was found that fitting to the projections and fitting over the two dimensional plane generally determined the fitted variables with similar precision. The fits discussed here were therefore made to the projections, since systematic errors were easier to estimate in that case. The measured total cross section ratios were included in the fits only where indicated.

We now discuss these fits in detail. We first consider the muon variables in Section 4.2.1. In Section 4.2.2, we consider effects that alter primarily the y distribution alone (changes in the sea, or in σ_L/σ_T). In Section 4.2.3 we consider effects primarily on the central part of the x distribution alone, such as softening of the neon valence distribution, and comparison with other published results for this region. In Section 4.2.4 we consider the effects on the combined distributions while Section 4.2.5 also includes

the measured cross section ratio as additional data. Readers wishing to go directly to the final results should now turn to Section 5.

4.2.1 Fits to the Ratio of the Muon Variable Distributions

Assuming there is no difference between the muon variable distributions for neon and deuterium, then a constant ratio gives an acceptable fit to the four data sets (see Figure 1 and Table 4, Fit A). Also shown in Figure 1 is the prediction for v_μ and p_μ^T ratios using parameters from the fit to the x and y distributions discussed below (Table 4, Fit P). It should be noted however that the ratios of the muon variables do not constrain the particular quark model parameters ($d\bar{s} \sim 0.2$, $f_s \lesssim 1$) as well as the ratios of the x and y distributions (compare Fit C with Fit O in Table 4).

4.2.2 Fits to the Ratio of y Distributions

The ratio of y distributions measures differences in the sea quark distributions, relative to the valence quark distributions, averaged over x. The data is indeed sensitive to the sea since allowing the amount of neon sea to differ reduces the χ^2 significantly, by 4.8 for one additional parameter; the data indicate f_s is below 1, ie some reduction in the neon sea distribution (Fit E).

We can also examine whether the data require an additional (1-y) contribution in the neon, ie a different R value, without specifying the neon sea contribution. Taking R_D to be $0.112^{[2]}$, one finds R_{Ne} to be about the same as R_D (Fit F, with no significant improvement in χ^2). If a more complex form for R_D is used^[17] the conclusion remains the same (Fit G). In both cases the conclusions about the reduction in the neon sea distribution remains unchanged.

It had been suggested^[15] that our original conclusions^[5] that the amount of sea in neon was incompatible with a $\sim 30\%$ increase^[14], could be avoided if $R_{Ne} \neq R_D$. However, introducing an extra (1-y) contribution for the anti-neutrino neon data that is sufficiently large to do this leads to inconsistencies with the neutrino y distribution^[9]. A sea level 30% larger in neon than in deuterium, as suggested by various models following the original EMC data^[1], is excluded by 4.8 standard deviations (Fit H with an increase in χ^2 from 23 to 46).

4.2.3 Fits to the Ratio of x Distributions Between 0.2 and 0.6.

The data with x between 0.2 and 0.6 is seen to have a significant slope in the SLAC electron data, and for muon scattering. In the present neutrino and antineutrino data, this region (ten data points) can be considered compatible with no difference between the neon and deuterium x distributions (Fit I). However, if the neon valence quark distribution is allowed to vary, there is a decrease in χ^2 of 3 for one additional parameter (Fit J), $d\beta = 0.2 \pm 0.1$.

The data from SLAC^[2] provide precise measurements for electron scattering for x above ~ 0.15 . Taking the mean of the SLAC results for carbon and aluminium to represent neon and comparing with the present data in the restricted x region (x between 0.2 and 0.6) reduces χ^2 by about the same amount (Fit K).

A similar reduction in χ^2 is obtained when using typical recent theoretical calculations^[18,19] (Fit L).

4.2.4 Fits to the Ratio of Both x and y Distributions.

If the valence distribution for neon is allowed to soften ($d\beta > 0$) and the neon sea to change, there is a significant reduction in χ^2 of 11 for two additional parameters (Fit N, dotted line in Figure 3). The resulting values for $d\beta$ and f_s are strongly anti-correlated.

Thus the differential distributions are well described by adjusting $d\beta$ and f_s . However, Fit N predicts that the total cross sections for neutrino (antineutrino) neon interactions are 8% (14%) less than for the corresponding deuterium interactions. This is inconsistent with the measured values (see Table 1).

4.2.5 Fits to the Ratio of x and y Distributions and the Total Cross Section Ratio

Allowing $d\alpha$ also to vary permits consistency with the total cross section ratios in Table 1. Furthermore these values may be included as two further constraints which the data should satisfy (Fit T giving the dashed line in Figure 3). The resulting fitted error on $d\beta$ is larger, while the precision on the estimate of the sea in the neon is little altered. After this fit the parameters $d\alpha$ and $d\beta$ describing the neon valence quark distribution are highly correlated; however the correlation of $d\beta$ with the decrease in the sea is much reduced as compared to Fit N. The small differences in shape between

this fit (T) with α_{Ne} free and that with α_{Ne} fixed (N) can be seen by comparing the dashed and dotted lines in Figure 3.

It has been proposed^[20] that the quark distribution in nucleons is 'rescaled' as A increases, as if the scattering from nucleons in higher A nuclei corresponds to higher Q^2 scattering from free nucleons. For such a model one may expect $d\beta > 0$, $d\alpha < 0$, $d\alpha/d\beta \sim -0.2$ ^[21]. However since there is both no significant increases in the sea in neon, and no significant change in the total cross section, then $d\alpha/d\beta$ is in fact positive for Fit T. If $d\alpha/d\beta$ is constrained to be -0.2, then the fitted χ^2 increases by 4, equivalent to two standard deviations.

The Fit T suggests some decrease in the neon sea (also seen in fits discussed in 4.2.2). However, if one assumes $R_{\text{Ne}} = R_{\text{D}}$ and $d\gamma = 0$, then the fitted sea contribution decreases by only (7±6)% (see Fit Q and Fit R where $R_{\text{Ne}} = R_{\text{D}}$ and $d\gamma$ is free).

The parameter $d\gamma$, describing the change in shape of the sea, is fairly loosely determined by these fits: the uncertainty in $d\gamma$ is an order of magnitude larger than that in $d\beta$. It is the only parameter that is much better determined by fitting to the 2-dimensional x-y plane instead of the x and y projections. Repeating Fit T using the 2-dimensional x-y plane gives $d\gamma = -0.3 \pm 0.5$ (statistical error only). Assuming there is no significant difference in γ between neon and deuterium, Fit T becomes Fit S and f_s is closer to 1.

5. Discussion

The final result of this analysis in its most general form is the result of Fit T in Table 4. Fits P and U repeat Fit T with other cuts in Q^2 , namely for all Q^2 and for Q^2 above 4.5 GeV² instead of for Q^2 above 1 GeV². It can be seen that the fitted parameters are insensitive to the Q^2 cut used.

The following summarises the results of the detailed fits.

- (i) Our x distribution ratios are in agreement with the SLAC and BCDMS data and require $d\beta$ to be non-zero at nearly the two standard deviation level. The x and y distributions taken together indicate that there

are measurable differences in the quark distributions at the 3 standard deviation level.

- (ii) It is the fact that the observed total cross section ratio is not some (8 to 14)% below unity that requires d_u to be also non-zero and, indeed, positive.
- (iii) d_u and d_s are strongly correlated. In order to see if the positive sign of d_u is compatible with other data one might include the measurements for carbon or aluminium from SLAC^[2], or nitrogen from BCDMS^[3]; then d_u/d_s becomes ~ 0.08 , ~ -0.01 or ~ 0.16 respectively.
- (iv) For given f_R , the ratio f_s of the sea contributions is largely determined, relative to the integrated valence contributions, by the ratio of the y distributions alone.

It can be seen from Table 4 that only the valence parameters, α and β and the amount of sea differ between neon and deuterium. The other parameters (γ and R) are found to be equal in neon and deuterium within about one standard deviation and setting them to be equal increases χ^2 insignificantly.

The fits all assume some particular form for R . Unfortunately no form is well established experimentally; however the fit results are insensitive to the form chosen.

6. Conclusions

A careful comparison has been made of both neutrino and antineutrino interactions in neon and deuterium targets in precisely controlled experimental conditions using some 40,000 events divided evenly between the two targets.

The results agree with previous neutrino and antineutrino scattering results, and are the most precise available.

At the lowest values of Q^2 some decrease in the neon cross section, consistent with shadowing, is observed for the first time in neutrino interactions. This observation will be discussed in detail elsewhere^[13].

No significant variation with Q^2 in the neon to deuterium cross-section ratio is seen for Q^2 above 1 GeV² (the data extend up to ~ 30 GeV²). It is therefore the data with Q^2 above 1 GeV² that have been analysed in detail here.

Measuring the ratio of the total and differential cross sections for all events provides new constraints on models of the EMC effect. The conclusions are as follows:

- The ratios of (anti)neutrino nucleon total cross sections determined for neon to that for deuterium indicate that the gluon momentum fraction as well as the quark momentum fraction per nucleon is the same in the two targets to within about $\pm 4\%$.
- The ratio of x distributions for x between 0.2 and 0.6 indicates a decrease similar to that observed in electron and muon scattering off similar targets. This softening of the neon valence quark distribution corresponds to β_{Ne} being larger than β_{D} by 0.2 ± 0.1 if α is assumed to be unchanged.
- The ratio of y distributions rules out the significant increase in the sea in neon required by some early models of the EMC effect. Allowing $R = \sigma_{\text{L}}/\sigma_{\text{T}}$ to be A dependent does not save these models: the data indicate that R_{Ne} and R_{D} are not significantly different.
- The shape and normalisation prefer both β_{Ne} to be (0.5 ± 0.2) larger than β_{D} , while $(\alpha_{\text{Ne}} - \alpha_{\text{D}}) \sim + (0.2 \pm 0.1) (\beta_{\text{Ne}} - \beta_{\text{D}})$. However $d\alpha \sim -0.2 d\beta$ is only excluded at two standard deviations.
- The shape of the sea in neon is not significantly different from deuterium ($d\gamma \sim 1 \pm 1$). The fraction of sea in neon is measured to be $(7 \pm 6)\%$ or $(18 \pm 10)\%$ less than in deuterium, depending on the model for $\sigma_{\text{L}}/\sigma_{\text{T}}$ and $d\gamma$.

Many models of the EMC effect have differentiated between a 'large' x region ($x \gtrsim 0.2$) and the small x region. Analysis of these neutrino data allows both a complete investigation of the whole x region (excepting that dominated by Fermi motion effects) and simultaneously also of the y distributions and total cross sections.

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TABLE 1**Some Parameters for the Total Deuterium and Neon Event Samples**

	Antineutrino		Neutrino	
	D	Ne	D	Ne
Number of Selected CC Events with $p_{\mu} > 5$ GeV	9999	12856	6778	7662
Scan Efficiency	0.91 ± 0.02	0.94 ± 0.01	0.95 ± 0.01	0.95 ± 0.01
Reconstruction Efficiency	0.97	1	0.97	1
Fully Corrected Number of CC Events	11260	13430	7360	8135
Number of NC Background Events	13	20	9	8
Ratio $\sigma(\text{Ne})/\sigma(\text{D})$ of cross sections per nucleon	$1.02 \pm 0.02 \pm 0.05$		$1.01 \pm 0.02 \pm 0.02$	
C (Hadron Energy Correction Factor)	1.63 ± 0.02	1.72 ± 0.02	1.57 ± 0.02	1.67 ± 0.02
Mean Beam Energy in GeV	41		56	
Mean Q^2 in GeV^2	5		9	

Table 3(a)

Ne/D Ratios vs x for $15 < E_\nu < 160$ GeV, Statistical and Systematic Errors
(Normalised to 1 for the Total Data Sets in Table 1)

$Q^2_{\min}$ (GeV) ²	$x = 0.00-0.05$	$0.05-0.10$	$0.10-0.15$	$0.15-0.20$	$0.20-0.25$	$0.25-0.30$	$0.30-0.40$	$0.40-0.50$	$0.50-0.60$
0.0 ν Ratio	0.925	0.984	0.990	1.062	0.989	1.003	1.029	0.914	0.865
Statistical Error	0.055	0.052	0.051	0.056	0.056	0.060	0.051	0.057	0.069
Systematic Error	0.011	0.003	0.005	0.005	0.007	0.006	0.005	0.006	0.018
$\langle Q^2 \rangle$ GeV ²	1.3	3.8	6.0	8.0	10.6	12.9	15.6	16.7	18.0
1.0 ν Ratio	1.132	0.996	1.021	1.088	0.986	0.960	1.012	0.891	0.855
Statistical Error	0.103	0.060	0.057	0.060	0.057	0.059	0.051	0.057	0.070
Systematic Error	0.018	0.007	0.005	0.003	0.002	0.004	0.008	0.016	0.020
4.5 ν Ratio	1.082	0.936	1.035	1.121	1.009	0.928	1.040	0.902	0.865
Statistical Error	0.274	0.092	0.079	0.080	0.070	0.066	0.059	0.063	0.079
Systematic Error	0.080	0.043	0.025	0.014	0.003	0.006	0.020	0.035	0.045
0.0 $\bar{\nu}$ Ratio	0.995	0.968	0.959	1.035	1.048	1.031	0.989	0.972	0.964
Statistical Error	0.042	0.038	0.039	0.046	0.049	0.054	0.044	0.053	0.067
Systematic Error	0.012	0.004	0.007	0.012	0.017	0.016	0.016	0.017	0.017
$\langle Q^2 \rangle$ GeV ²	1.0	2.6	3.9	4.8	6.0	6.9	8.0	8.6	8.9
1.0 $\bar{\nu}$ Ratio	0.981	0.995	0.982	1.039	1.042	1.025	1.005	0.971	0.988
Statistical Error	0.071	0.046	0.044	0.050	0.051	0.056	0.046	0.055	0.071
Systematic Error	0.007	0.005	0.006	0.010	0.009	0.010	0.011	0.011	0.010
4.5 $\bar{\nu}$ Ratio	0.836	0.914	0.950	1.096	0.993	0.987	1.022	0.947	0.931
Statistical Error	0.209	0.088	0.072	0.080	0.070	0.072	0.061	0.068	0.086
Systematic Error	0.117	0.071	0.045	0.026	0.017	0.020	0.015	0.015	0.016

TABLE 3(b)

Ne/D Ratios vs y for $15 < E_\nu < 160$ GeV and $x < 0.6$, see 3(a)

$Q_{\min}^2$ (GeV) ²	$y =$	0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1
0.0 ν	Ratio	0.925	0.949	0.971	1.042	0.972	0.978	0.908	1.012	1.190
	Statistical Error	0.052	0.051	0.052	0.058	0.053	0.055	0.051	0.063	0.082
	Systematic Error	0.023	0.011	0.004	0.008	0.007	0.009	0.008	0.012	0.017
1.0 ν	Ratio	0.931	0.914	0.970	1.076	0.981	1.002	0.910	1.021	1.193
	Statistical Error	0.082	0.055	0.055	0.062	0.055	0.058	0.052	0.065	0.082
	Systematic Error	0.016	0.007	0.003	0.005	0.011	0.007	0.003	0.005	0.014
4.5 ν	Ratio	0.763	0.872	1.017	1.021	0.976	0.988	0.882	0.997	1.177
	Statistical Error	0.197	0.097	0.083	0.076	0.067	0.067	0.056	0.068	0.085
	Systematic Error	0.025	0.021	0.011	0.011	0.012	0.007	0.006	0.016	0.032
0.0 $\bar{\nu}$	Ratio	0.987	0.987	1.019	1.000	1.069	0.978	0.959	1.003	0.812
	Statistical Error	0.039	0.035	0.039	0.041	0.049	0.050	0.054	0.071	0.071
	Systematic Error	0.036	0.015	0.017	0.011	0.010	0.012	0.014	0.029	0.038
1.0 $\bar{\nu}$	Ratio	1.077	0.990	1.045	1.003	1.070	0.956	0.967	0.987	0.815
	Statistical Error	0.066	0.041	0.044	0.044	0.052	0.051	0.057	0.072	0.074
	Systematic Error	0.028	0.021	0.016	0.013	0.008	0.008	0.017	0.029	0.040
4.5 $\bar{\nu}$	Ratio	1.170	0.997	1.052	1.004	1.016	0.971	0.951	0.965	0.809
	Statistical Error	0.264	0.089	0.073	0.064	0.065	0.066	0.070	0.087	0.083
	Systematic Error	0.016	0.019	0.015	0.012	0.014	0.018	0.028	0.071	0.087

TABLE 4

The Information Obtained from the Fits to the Ne/D Ratios of Differential Distributions

Data	$Q_{\min}^2$ (GeV) ²	Fit	Hypothesis	$d\beta$	$d\alpha/d\beta$	$d\gamma$	f_s	f_R	χ^2	NDF
$\nu \mu^+ p_\mu$ (see section 4.2.1)	0	A	No difference in Ne, D distributions	0	0	0	1	1	27.6	38-2
	0	B	$d\beta, R_g$, from Fit 0	0.23	0	0	0.82	1	26.6	"
	0	C	Ne valence β and Ne sea unknown	0.15 ± 0.12	0	0	0.88 ± 0.14	1	26.0	38-4
Y (see section 4.2.2)	1	D	No difference in Ne, D distributions	0	0	0	1	1	23.2	18-2
	1	E	Ne Sea different from D sea	0	0	0	0.82 ± 0.08	1	18.4	18-3
	1	F	Ne sea different from D sea $R_D = 0.112, R_{Ne} \neq R_D$	0	0	0	0.82 ± 0.08	0.6 ± 0.7	18.1	18-4
	1	G	Ne sea different from D sea $R_D = 0.73(1-x)^{3.7}/\ln(Q^2/0.24^2)$	0	0	0	0.82 ± 0.08	0.9 ± 1.0	18.4	"
	1	H	$R_D = 0.112, R_D \neq R_{Ne}$ Ne sea = 1.3 D sea (see text)	0	0	0	1.3	1.6 ± 0.7	45.9	18-3
0.2 < x < 0.6 (see section 4.2.3)	1	I	No difference in Ne, D distributions	0	0	0	1	1	5.7	10-2
		J	Softening of Ne valence distribution	0.20 ± 0.11	0	0	1	1	2.3	10-3
	1	K	SLAC '83 data shape imposed (Ref 2)	-	-	-	-	-	2.5	10-2
	1	L	Akulnischev et al shape imposed (Ref 18) Efremov shape imposed (Ref 19)	-	-	-	-	-	2.6 2.4	" "

TABLE 4 (continued)

Data	$Q_{\min}^2$ (GeV) ²	Fit	Hypothesis	$d\beta$	$d\alpha/d\beta$	$d\gamma$	f_s	f_R	χ^2	NDF
$0 < x < 0.6$ & y (see section 4.2.4)	1	M	No difference in Ne, D data	0	0	0	1	1	36.8	36-2
	1	N	Ne valence softens, and sea changes	0.32 ± 0.10	0	0	0.78 ± 0.07	1	25.3	36-4
	0	O	Ne valence softens and sea changes	0.23 ± 0.09	0	0	0.82 ± 0.06	1	23.5	"
All data										
$0 < x < 0.6$ & y norms (see section 4.2.5)	0	P	All parameters free, $R_D = 0.112$	0.47 ± 0.19	0.22 ± 0.06 -0.07	0.7 ± 0.9	0.88 ± 0.10	1.1 ± 0.5	22.0	38-5
	1	Q	$d\gamma = 0, f_R = 1$	0.40 ± 0.16	0.19 ± 0.05	0	0.93 ± 0.06	1	30.1	38-3
	1	R	$f_R = 1$	0.48 ± 0.18	0.22 ± 0.04	0.9 ± 0.9	0.89 ± 0.07	1	28.8	38-4
	1	S	$d\gamma = 0$	0.36 ± 0.16	0.14 ± 0.08 -0.13	0	0.90 ± 0.07	1.4 ± 0.6	29.4	"
	1	T	All parameters free, $R_D = 0.112$	0.46 ± 0.19	0.16 ± 0.06 -0.09	1.3 ± 1.2	0.82 ± 0.08	1.6 ± 0.6	27.4	38-5
	4.5	U	"	0.46 ± 0.22	0.20 ± 0.06 -0.11	0.4 ± 1.5	0.86 ± 0.11	1.3 ± 0.7	21.6	"

FIGURE CAPTIONS

Figure 1 The ratio for neutrino and antineutrino data of the Ne and D cross sections per nucleon as functions of ν_μ and p_μ^T , for $15 < E_\nu < 160$ GeV. The dashed curve shows the prediction of Fit P (see Table 4 and text) for these variables.

Figure 2 The ratio for neutrino and antineutrino data and their parity conserving combination of the Ne and D cross sections per nucleon for all Q^2 and $15 < E_\nu < 160$ GeV as functions of x and y . The dashed curve shows the result of Fit P (see Table 4 and text).

Figure 3 The ratio for neutrino, antineutrino data and the parity conserving combination (crosses are data from Arnold et al.^[2] for A1) of the Ne and D cross sections per nucleon for $Q^2 > 1$ GeV² and $15 < E_\nu < 160$ GeV as functions of x and y . The dotted (dashed) curve shows the result of Fit N (Fit T) (see Table 4 and text).

Figure 4 The ratio for neutrino, antineutrino data and the parity conserving combination (triangles are data from Bari et al.^[3] for N) of the Ne and D cross sections per nucleon for $Q^2 > 4.5$ GeV² and $15 < E_\nu < 160$ GeV as functions of x and y . The dashed curve shows the result of Fit U (see Table 4 and text).

Figure 5 The ratio for neutrino and antineutrino data of the Ne and D cross sections per nucleon as functions of Q^2 for various regions of x , ($15 < E_\nu < 160$ GeV, note scale change at $Q^2 = 1$ GeV²).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5