BACKWARD PARTICLE PRODUCTION IN NEUTRINO NEON INTERACTIONS

BEBC WA59 Collaboration

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ABSTRACT

Backward proton and pion production is studied in ν and $\bar{\nu}$ charged current interactions in neon. The results are compared with other experiments and theory. The complete backward proton data is compatible with protons produced by reinteractions in the nucleus. However after selecting data with fewer reinteractions, muon variables appear correlated to those for the backward proton, as expected by the two-nucleon correlation model.

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1. Introduction

Secondary protons from interactions on a free nucleon target cannot go backwards. Many experiments (summarized in references 1 to 4) have used backward particle production as a tool to investigate nuclear structure. Selecting events with fast backward protons may allow studies of the high momentum tail of the Fermi momentum distribution arising, perhaps, from short range nucleon-nucleon correlations in the nucleus. From another point of view, experiments in deep inelastic lepton nucleon scattering have shown that nuclear structure functions deviate from the corresponding ones for the free nucleon (the EMC effect, reviewed in reference 5). According to some of the models which have been proposed to explain this effect, Fermi motion and nuclear binding play an important role^(6,7), while other authors have emphasised the additional role of correlations between nucleons⁽⁸⁾: these might be better understood from a study of backward proton production.

Two main classes of models have been put forward to explain the fast backward proton production:

- two-nucleon correlation (or short-range order) models^(9,10) suggest that the high momentum backward protons (sometimes called cumulative protons) arise from correlations between two (or more) nucleons inside the nucleus (called two, three or four nucleon clusters).
- reinteraction (also called multiple scattering or intranuclear cascade) models suggest that the backward protons result from successive rescattering processes inside the target nucleus⁽¹¹⁾, including intranuclear absorption of slow pions⁽¹²⁾.

Some of the predictions of the two-nucleon correlation model (discussed in section 2) are not expected in other models. Antineutrino data⁽¹³⁾, with a neon hydrogen mixture for the target, gave evidence for two-nucleon correlations. On the other hand neutrino data⁽¹⁴⁾, with a higher average atomic number for the target (CF_3Br), were consistent with nuclear reinteractions being responsible for the backward protons. If both two-nucleon correlation effects and reinteraction effects are present in the data, we see no way to further separate the multi-nucleon correlations.

This paper presents data on backward proton and backward charged pion production in neutrino and antineutrino charged current interactions on neon. The results for backward protons are compared with the expectations of the reinteraction model and the two-nucleon correlation model - taking deuterium data to represent the pure two nucleon case in the same conditions. There are also comparisons with other experiments. Further details may be found in reference 15.

The next section presents a summary of the predictions for the two-nucleon correlation model. Section 3 provides details concerning the data. Section 4 presents the backward particle efficiencies and kinematical distributions. Section 5 compares the data with the reinteraction model and section 6 with the two-nucleon correlation model. Section 7 presents our conclusions.

2. The Two-Nucleon Correlation Model

The simplest two-nucleon correlation model represents target nucleons as sometimes having a partner which is related to the target like the spectator in deuterium. For example in neutrino charged current (CC) interactions the backward (spectator) proton would be correlated with the produced muon if significant two-nucleon correlations exist. The spectator and target are usually assumed to have initial values of $E - p_L$, whose sum is constrained to be the mass of two nucleons, $2m$, (p_L is the momentum component in the direction of the neutrino beam). As the backward proton (spectator) takes more of the initial $E - p_L$ there is less for the target nucleon and therefore less for the secondary particles, including the muon. The target nucleon is taken to be off the mass shell in order to conserve the energy and momentum in the scattering process.

The predicted $E - p_L$ correlations may be written in terms of the Bjorken scaling variables x , y and $v = xy$. The four vector of the incident neutrino is $[p_\nu] = (E_\nu, 0, 0, E_\nu)$. The spectator, usually assumed to be the backward proton, has the four vector $(\vec{p}_s, E_s)$, longitudinal momentum $p_{L,s}$ and

is assumed to have the nucleon mass. The target nucleon has the four vector $[p_{tar}] = (-\vec{p}_s, E_{tar})$ and longitudinal momentum $p_{l,tar}$: it takes the remaining energy of the two-nucleon system, $E_{tar} = 2m - E_s$. Conservation of $E - p_l$ for the two-nucleon system gives

$$2m = (E - p_l)_s + (E - p_l)_{tar}$$

so that $(E - p_l)_{tar}/m = 2 - \alpha$ where $\alpha = (E - p_l)_s/m$ is a commonly used variable in analyses of backward particle data.

The scaling variable v for an interaction with a moving target is

$$v_{true} = \frac{Q^2}{2[p_{tar}] \cdot [p_\nu]} = \frac{Q^2}{2(E_{tar}E_\nu - p_{l,tar}E_\nu)} = \frac{Q^2}{2E_\nu(E - p_l)_{tar}}$$

The measured value of v assuming a stationary target is

$$v_{meas} = \frac{Q^2}{2mE_\nu} = \frac{(E - p_l)_{tar}}{m} v_{true} = (2 - \alpha)v_{true} \quad (1)$$

Thus the true scaling variable, v_{true} , is related to the measured quantity for the muon $v_{meas} = v_\mu \simeq (E - p_l)_\mu/m$ by the kinematic factor $\left(\frac{1}{2-\alpha}\right)$.

Furthermore with a moving target

$$y_{true} = \frac{[p_{tar}] \cdot [q]}{[p_{tar}] \cdot [p_\nu]} = \frac{E_{tar}\nu - p_{l,tar}q_l - \vec{p}_{t,tar} \cdot \vec{q}_t}{E_{tar}E_\nu - p_{l,tar}E_\nu}$$

where $[q]$ is the four momentum transferred to the target and the variable ν is the leptonic energy transfer in the laboratory. Assuming a stationary target

$$y_{meas} = \nu/E_\nu = \left(\frac{(E - p_l)_{tar}}{E_{tar} - p_{\vec{q},tar} \sqrt{1 + Q^2/\nu^2}} \right) y_{true} \quad (2)$$

where $p_{\vec{q},tar}$ is the target proton's momentum component in the direction of the momentum transfer, $\vec{q}$.

Since $v = xy$, the scaling variable x is related to the measured value by :

$$x_{meas} = \frac{E_{tar} - p_{\vec{q},tar} \sqrt{1 + Q^2/\nu^2}}{m} x_{true} \quad (3)$$

In order to satisfy equation (1) we use the neutrino direction to define α , while in comparisons of backward proton angular distributions with results from hadron beams we use the $\vec{q}$ direction. For y there is no single choice of the system for the measurement of p_l . In practice we find that this distinction makes little difference: we discuss it here since some other authors have used the $\vec{q}$ direction exclusively. In neutrino experiments the beam direction (but not the energy) is well measured for each event, as are the muon variables. In contrast x , y and $\vec{q}$ depend on reconstructing the hadronic final state. Since typical errors on the transverse momenta of the hadron shower are at least as big as the Fermi momentum, the $\vec{q}$ direction becomes poorly known for small Q^2 . In order to reduce such errors the measured hadron shower direction can be used for the $\vec{q}$ direction. Also the measured hadron shower momentum can be selected to be above some minimum so that the error on the direction is not too large.

Backward protons, labelled Bp by many authors, have α above 1, as p_l is negative. According to (1) the mean measured value of v_μ for the events with backward protons, $\langle v_\mu \rangle_{Bp}$, should decrease linearly as α increases. Many authors normalise $\langle v_\mu \rangle_{Bp}$ by the mean v for all events, and show $v_N = \langle v_\mu \rangle_{Bp} / \langle v_\mu \rangle$.

3. The Experimental Data

The neon data used in this experiment (CERN experiment WA59) come from an exposure of BEBC (the Big European Bubble Chamber) to the wide band antineutrino and neutrino beams generated by 400 GeV protons from the CERN SPS. BEBC was filled with a 75-mole per cent neon-hydrogen mixture. Deuterium data (CERN experiment WA25) have already been compared in detail with neon data⁽¹⁶⁾; here they are used to quantify the predictions of the two-nucleon correlation model in the same experimental conditions (see section 6).

The muons from neutrino charged current interactions were selected by the External Muon Identifier (EMI). The geometric and electronic efficiencies for muon identification are high for muons of momentum greater than 5 GeV/c, which was the minimum muon momentum considered in the analysis. The secondaries from charged current events (including protons with momenta above 350 MeV/c) were fully measured. Secondary neutron interactions and backward protons were not included in the evaluation of the observed hadron momentum vector. Secondary neutrons are not detected efficiently and so could not be used in this analysis (their interactions are not distinguishable from K_L^0 interactions, and are hard to associate unambiguously to the primary rather than to a secondary interaction.)

Backward and forward tracks are defined with respect to the neutrino beam direction in the laboratory, except for the comparisons with hadron data.

Further experimental details for the neon data are given in reference 17, while the protons seen in the deuterium are analysed in reference 18. A summary of event numbers and backward particle rates is given in table 1.

4. Backward Particle Sample

Selection and detection efficiency. Protons that stop in neon without interacting show a well defined relationship between range (above 4cm) and curvature and can be unambiguously identified. (Heavier charged nuclear fragments generally have shorter ranges and are not identified.) Protons with momenta between 350 and 800 MeV/c were used: lower momentum protons (below 350 MeV/c) are often called 'stubs' and attributed to nuclear breakup. All other positive tracks were called π^+ candidates. Backward proton momenta above about 350 MeV/c can only be attributed to scattering processes or tails of the Fermi momentum distribution.

The proton identification efficiencies in neon (shown in figure 1) were measured in the following manner. For our isoscalar liquid, real π^+ tracks, of a given momentum, will have the same length distribution as the π^- of the same momentum. Any unidentified protons (with the same momentum) will have lengths only up to the proton range for that momentum. Thus the excess tracks in the ' π^+ ' sample (compared with the π^- sample of the same momentum) with lengths below the proton range are attributed to unidentified protons. This method was used (in several small momentum intervals) until the statistics in the π^- sample became too small - above 800 MeV/c. The protons were further weighted to allow for losses due to such early interactions that the curvature of the track (charge) could not be measured. This procedure does not assume any equality of the shapes of the real π^+ and π^- momentum distributions. A sample of π^+ free from unidentified protons was obtained by taking only those positive tracks (at each momentum) with length too great to be due to protons. The efficiency for this selection was determined from the fraction of π^- that pass the same selection and is also shown on figure 1. The π^+ and π^- were also weighted to allow for losses due to early interactions. Any backward charged kaons are included as pions.

For the remainder of this paper the proton and pion differential distributions from the neon data are weighted to correct for these identification efficiencies whose means for backward particles are 87% for protons, 76% for π^+ and 91% for π^- .

The protons in deuterium were identified by the track stopping in the liquid (at lower momenta) and the visible ionisation. We corrected the backward particle data from deuterium for ambiguities

due to very steep tracks making angles less than 45° with the mean optic axis, or early interactions (before 20cm) on tracks over 350 MeV/c. Backward protons with momenta between 150 and 800 MeV/c were available. For the fits to the differential distributions we used the same momentum interval as in the neon (350 to 800 MeV/c.) However, in order to have useful statistics, we included the whole deuterium backward proton sample (150 to 800 MeV/c) for the studies of the scaling variable correlations with α .

The weights clearly change the slopes of the momentum distributions. However the data plotted for the main test of the two-nucleon correlation model, v_N as a function of α (discussed in section 6), are not changed significantly by the weights.

Backward particle differential distributions. Figure 2 shows the normalised invariant p^2 distributions of the backward particles for both beams combined. The normalised invariant differential cross section for backward particle production can be fitted as:

$$\frac{1}{N_{ev}} \frac{E}{p} \frac{dN}{dp^2} = C \exp(-B(\theta)p^2) \quad (4)$$

where E and p are the energy and the momentum of the backward particle respectively and θ is the angle between the particle direction and the beam direction.

The lines shown on figure 2 are fits of equation (4) to the data averaged over the whole backward region (events with only one proton are also shown on figure 2(a), as discussed in section 6.) Table 2 shows our fitted values of the slope parameter B . The second error shown (for the protons and π^+ in neon) is the systematic error on B due to the error in the detection efficiency: this small contribution is ignored elsewhere. It is interesting to note that the B parameters describing the backward π^+ and π^- momentum distributions (Table 2) are not different from those for backward protons. The backward proton slope for neon increases by about a standard deviation if the $\vec{q}$ direction (approximated by the measured hadron shower direction) is used to define forwards instead of the neutrino beam direction. Also a change in the slope is seen on figure 2(a) for deuterium at $p^2 \sim 0.1(\text{GeV}/c)^2$, near the minimum momentum used for heavy targets. Thus the minimum momenta in different experiments may affect the fitted slopes. For momenta above 350 MeV/c, the deuterium data give $B = 12.8 \pm 2.0(\text{GeV}/c)^{-2}$.

It is indicated in the literature that the slope parameter $B(\theta)$ for protons increases with θ but is rather independent of the mass number of the target nucleus, as well as of the type and energy of the incident particle. The angular dependence of the slope B (for protons) is shown in figure 3. Here θ is the angle with respect to the $\vec{q}$ direction (approximated by the measured hadron shower direction, for events with hadron showers with measured momenta over 1 GeV/c to avoid data with very poor resolution on θ). This choice for θ coincides with the definition for hadron beam experiments, and is similar to other neutrino experiments. The curve is a fit to the polynomial expansion $a + b\cos\theta + c\cos^2\theta$, similar to that shown in reference 12.

The energy dependence of the slope parameter B (for protons) is shown in figure 4 averaged over the whole backward region. The energy is the corrected laboratory hadron shower energy: we assume this is approximately equivalent to the beam energy in hadron experiments. We see no variation of B with energy. Our data span a range in hadron energy that was only available from different experiments^(13a): our values for neon lie within the range 10 to 14 obtained previously.

5. The Data and the Reinteraction Model

In the reinteraction (or intranuclear cascade) model the backward protons are produced by one or more rescatters inside the nucleus. Such models predict events with several forward protons above 350 MeV/c; these are seen in the data. The backward proton events also exhibit features expected from several reinteractions, because the more forward protons there are, the more backward protons are produced. Indeed, figure 5 indicates that the average multiplicity of the backward protons

increases with the number of the forward protons observed, for both the neutrino and antineutrino beams as seen previously^(14b) for neutrinos.

A further prediction of the reinteraction model is that α (for the backward proton) will not be related to v_μ because the target nucleon is not related to the backward proton. In order to compare with previous results, we show the normalised average v_μ (called v_N in the following) plotted against α in figure 6(a) and (c) for both the neutrino and the antineutrino data. It can be seen that as α of the backward proton increases, the muon share remains roughly constant, in agreement with the reinteraction model.

One of the mechanisms proposed for the backward proton production in the framework of the reinteraction models is the absorption of slow pions by two nucleons - discussed in reference 14b. On average, π^+ absorption produces at least three times as many protons as π^- absorption. Moreover the absorption cross section has a maximum in deuterium for pion momenta around 250 MeV/c - this cross section is represented by the curve on figure 7(a). It is therefore suggested that events with protons from absorption should have fewer π^+ around this momentum. Figure 7 shows the ratio N_{π^-}/N_{π^+} in bins of the π momentum. The ratio increases at 250 MeV/c in the neutrino data as expected, but our antineutrino data do not confirm this. If the pion absorption were responsible for much of the backward proton production, it would also contribute to production of forward protons of similar momentum (between 350 and 550 MeV/c, rectangular points on figure 7). Our antineutrino data do not confirm that this model of absorption plays a significant, identified, role in N_{π^-}/N_{π^+} for neon.

Other rescattering mechanisms⁽¹⁹⁾ have been used for deuterium data⁽²⁰⁾ with real (or virtual) nuclear isobars in the intermediate state. In such a model the backward protons might be emitted after a neutrino interaction gives a slow Δ which interacts on another nucleon to give two nucleons - one going backwards. Such a mechanism might produce an enhancement in the proton-proton mass spectrum at about 2.2 GeV : we did not see any.

6. The Data and the Two-Nucleon Correlation Model

In this model the beam interaction occurs on one nucleon, the other correlated nucleon acting as a spectator during the process. If the target nucleon is moving forward before the interaction, the spectator nucleon is emitted in the backward hemisphere (because the two correlated nucleons have equal and opposite momenta). The consequences were outlined in section 2. In this model interactions producing several protons (above 350 MeV/c) may be attributed to the breakup of multi-nucleon correlations.

a) $E - p_l$ (or v_N) correlations. We looked at neutrino scattering on deuterium to see what to expect from two-nucleon correlations. Figures 6(b) and (d) show v_N plotted against α for neutrino and antineutrino deuterium data. As mentioned in section 4, the selected proton momenta are between 150 and 800 MeV/c - because the number of protons above 350 MeV/c is small. For α increasing from 1 to 1.5 the deuterium data reproduce the decrease in v_N expected by the two-nucleon correlation model, indicated by the line.

Figures 6(a) and (c) showed that v_N has only a small dependence (slope of the data points) on α for the complete samples of backward protons in neon. Thus the full samples of backward protons in neon show no clear evidence for two-nucleon correlations.

However, we can reduce the contributions from reinteractions in the neon nuclei by selecting events with just one detected proton. Figures 6(b) and (d) show v_N plotted against α for events with no more than one proton in the final state. Here the correlations seen in deuterium are partially reproduced in neon. The smaller decrease in neon of v_N as α increases is expected to arise both from residual single protons from reinteractions and from correlations between more than two nucleons. We do not detect neutrons, so that an interaction with just one observed backward proton may also have produced neutrons.

We estimate the significance of this correlation by fitting straight lines to the data on figure 6 (see Table 3.) The errors on the points shown in figure 6 are taken from the spread in the v_N values in each α bin. However for large α the statistics are small. For the fits the following procedure was therefore adopted. The errors are proportional to the mean v_N , and have been parameterised as $\frac{k \cdot v_N}{\sqrt{n}}$, (n is the number of backward protons at one α value, and k is about 1). With this error distribution the error in $\log(v_N)$ is constant, and $\log(v_N)$ is a variable with Gaussian errors. For these reasons the fits in table 3 minimise

$$\sum_{\alpha_i} \left(\frac{\log(v_{theory}) - \log(v_N)}{k/\sqrt{n}} \right)^2$$

where the sum is over the data points at different α values. In practice adopting this procedure made little difference.

It is easy to see that the neon data in figures 6a and 6c are fairly compatible with the line $v_N = 1$ (representing no effects), while the neon data with only one proton in figures 6b and 6d are not. Next we note that the fits (A and B) to the complete backward proton data sample with no correlation (slope zero but mean v_N unconstrained) are reasonable, but do improve when slopes are introduced (fits C and D).

After the selection of events with just one proton, the neutrino data show a marked preference for a negative slope (at some 3.1 standard deviations, compare fits E and G). The antineutrino data show the same trend (the slope is some 2.4 standard deviations from zero, compare fits F and H). If these proton samples in neon are assumed to consist of two subsamples, one with the two-nucleon correlation (as given by the deuterium data) and another sample with no correlations, then the fraction of protons with the two-nucleon correlation is obtained by the ratio of the slopes found in neon and in deuterium: the fraction is $(61 \pm 21)\%$ for neutrino and $(36 \pm 16)\%$ for antineutrino. In this calculation it has been assumed that the two subsamples of protons have identical α -distributions.

As can be seen from table 1, the rate of backward protons (or number of protons per charged current event) with momentum above 350 MeV/c from deuterium is 0.63% for neutrino and 0.21% for antineutrino. 34%(25%) of all neutrino (antineutrino) neon interactions have detected protons going forward. Using the above result for the fraction of protons with two-nucleon correlations and allowing for events with forward protons and the proton detection efficiency, the corresponding numbers for neon are $(3.6 \pm 1.2)\%$ for ν and $(1.6 \pm 0.7)\%$ for $\bar{\nu}$. Thus the rate of backward protons in neon with momenta above 350 MeV/c and showing the correlation is larger than in deuterium by a factor 6 ± 2 for ν and 7 ± 3 for $\bar{\nu}$.

b) y_B correlations. The two-nucleon correlations are predicted⁽⁴⁾ to have little effect on the y distribution. However the use of the Bjorken variables x, y reintroduces the question of how exactly they are measured in a neutrino experiment: the backward proton has been observed, but extra forward nucleons may be unidentified, and produced forward protons may be below the experimental lower momentum (350 MeV/c for the neon data.) Furthermore the target nucleon is off its mass shell. In order to avoid these problems we use the simple variable $y_{vis} = \sum_{hadrons} P_l / \sum_{hadrons+\mu} P_l$. In figure 8 the data suggest some slope for $\langle y_{vis} \rangle_{Bp}$ against α for neon, for events with just one detected proton. However the neon data are compatible with deuterium: we have not identified any experimental bias that causes this slope.

One may ask whether evidence for two-nucleon correlations has any implications for the EMC effect in neon. If we assume y is not correlated to α but v_μ is correlated, the same correlation holds for x . However the net x bias is small since the bias for the events with a forward moving target is approximately cancelled by events with a backward moving target. One would introduce a net bias only if one removed events with a backward nucleon from a data sample - indeed such a restriction could introduce biases up to about half of the EMC effect for neon.

c) Tail of the Fermi momentum distribution. The slopes observed in fits I and J to the deuterium data (Table 3) are somewhat steeper than the predicted slope of -1 (equation 1). If this difference

is assumed to be due to a statistical fluctuation then the fits G and H indicate that the fraction of backward protons in the neon 1-proton events showing two-nucleon correlations is $(90 \pm 26)\%$ for neutrino and $(69 \pm 24)\%$ for antineutrino (i.e. higher than the values $(61 \pm 21)\%$ and $(36 \pm 16)\%$ deduced above by direct comparisons of the neon and deuterium data). In either case, many of the remaining backward protons that are not correlated with the nucleon struck by the neutrino may be correlated with nucleons involved in reinteractions. This is supported by the fact that the B parameter describing the backward proton momentum spectrum (Table 2) is not different in events with only one backward proton.

Possible models of the tail of the initial particle Fermi momentum distribution (or, alternatively, final state interaction models) should give rates and distributions for the backward proton spectrum that are consistent with our observations. After correcting for detection efficiencies and selections, the fractions of events with a backward proton above 350 MeV/c attributed to the two-nucleon model (by fits G and H) are $(5.3 \pm 1.5)\%$ for neutrino and $(3.0 \pm 1.0)\%$ for antineutrino neon interactions. The ratio of neutrino to antineutrino fitted two-nucleon contributions is 1.8 ± 0.8 (and 1.4 ± 0.1 for the data without fitting.) These numbers compare well with the estimate⁽⁴⁾ of $(5 - 6)\%$ above 300 MeV/c for antineutrinos (which corresponds to some $(3 - 4)\%$ above 350 MeV/c) and a ratio of about 1.5.

Models of the shape of the high momentum tail of the Fermi distribution have included terms with powers of momenta, or extra exponential forms. An additional term proportional to p^{-4} at momenta higher than the Fermi momentum⁽²¹⁾ is awkward to reconcile with our backward proton data. Such a power law contribution does not fall as fast as the observed distributions in figure 2(a) : the distribution is clearly exponential.

Extra terms have been added to the Fermi distribution^(22,23) to model smearing of single nucleon structure functions to x between 1 and 1.4. Such terms may also be fitted to figure 2, in order to constrain their particular parameterisations. For example one form that has been used is⁽²²⁾

$$N(e^{-p^2/p_0^2} + \varepsilon_0 e^{-p^2/q_0^2} + \varepsilon_1 e^{-p^2/q_1^2})$$

where N is a normalisation constant, $p_0 = \sqrt{\frac{2}{5}} k_F$, k_F is the Fermi momentum, $\varepsilon_0 \simeq 0.03$, $q_0 \simeq \sqrt{3} p_0$, $\varepsilon_1 \simeq 0.003$ and $q_1 \simeq 0.5$ GeV/c. Fitting this form to figure 2 suggests ε_1 can be neglected, and $q_0 \simeq 299 \pm 5$ MeV/c.

7. Conclusions

We have presented data on backward particle production from interactions of neutrinos and antineutrinos in neon. The main results are:

- The invariant p^2 distributions of the backward protons are similar to those observed with other beams and targets. We note that the B parameters describing the backward pion momentum distributions (table 2) are not different from those for backward protons.
- As expected for protons from reinteractions in the neon nucleus, the complete sample shows no strong dependence of v_N on α (figure 6(a) and (c)). This is in agreement with reference 14, and in contrast to an earlier $\bar{\nu}$ -Ne experiment, reference 13.
- When we remove events with more than one proton (expected for intranuclear cascades), the neutrino and antineutrino data both show similar effects to deuterium, as expected from two-nucleon correlations (see figure 6(b) and (d)), in agreement with reference 13.

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	$\nu - \text{Ne}$	$\nu - \text{D}_2$	$\bar{\nu} - \text{Ne}$	$\bar{\nu} - \text{D}_2$
CC events selected	9520	22196	16536	15332
Mean $v_\mu, \times 10^4$	960 ± 10	998 ± 6	601 ± 5	611 ± 6
1 backward proton events	712	129	875	32
2 backward proton events	43	—	51	—
3 backward proton events	1	—	6	—
1 backward proton rate $\times 10^3$	85.3 ± 3.2	6.3 ± 0.7	60.3 ± 2.0	2.1 ± 0.5
2 backward proton rate $\times 10^3$	5.9 ± 0.5		4.0 ± 0.6	
Backward π^- rate $\times 10^3$	6.8 ± 0.9	1.0 ± 0.3	10.4 ± 0.8	4.4 ± 0.7
Backward π^+ rate $\times 10^3$	12.0 ± 1.3	3.7 ± 0.6	10.2 ± 0.9	1.6 ± 0.4
Events with 1 backward p and no other p	322		468	
D ₂ data: p with $150 < p < 350 \text{ MeV}/c$		665		227

Table 1: Summary of event numbers and rates, (p is short for proton). The data are for particle momenta above 350 MeV/c, except for the last line. The rates are the fraction of the events with a backward particle, divided by the mean detection efficiency. (The $\bar{\nu} - \text{D}_2$ rates include $\sim -14\%$ correction for missing CC with just a μ^+ , such events were included in $\bar{\nu} - \text{Ne}$.)

	$(\nu + \bar{\nu})$ -Ne data	$(\nu + \bar{\nu})$ -D ₂ data
Backward protons	$10.69 \pm 0.29 \pm 0.04$	12.8 ± 2.0
Backward π^+	$9.0 \pm 0.8 \pm 0.4$	17.0 ± 3.0
Backward π^-	10.4 ± 0.8	14.0 ± 3.1
1 backward p and no other p	11.2 ± 0.4	—

Table 2: The slope parameter $B(\text{GeV}/c)^{-2}$ from equation (4) for the lines fitted to the p^2 distributions in figure 2, for $p > 350\text{MeV}/c$. The second errors shown are the systematic errors due to the statistical precision on the identification efficiencies.

Fit	Data	χ^2	NDF	Slope	from Figure 6
A	$\nu - \text{Ne}$	11.3	7 - 1	0	a
B	$\bar{\nu} - \text{Ne}$	2.1	7 - 1	0	c
C	$\nu - \text{Ne}$	8.0	7 - 2	-0.36 ± 0.19	a
D	$\bar{\nu} - \text{Ne}$	0.7	7 - 2	-0.24 ± 0.20	c
E	$\nu - \text{Ne, 1proton}$	16.7	6 - 1	0	b
F	$\bar{\nu} - \text{Ne, 1proton}$	8.3	7 - 1	0	d
G	$\nu - \text{Ne, 1proton}$	6.4	6 - 2	-0.90 ± 0.26	b
H	$\bar{\nu} - \text{Ne, 1proton}$	1.5	7 - 2	-0.69 ± 0.24	d
I	$\nu - \text{D}_2$	3.7	8 - 2	-1.47 ± 0.29	b
J	$\bar{\nu} - \text{D}_2$	4.8	7 - 2	-1.90 ± 0.49	d

Table 3: Results of fitting straight lines to the α dependence of v_N . Fits E – H are for neon events with one backward proton and no forward proton.

Figure Captions.

Figure 1 Identification efficiencies for backward protons and π^+ , (with the length of the π^+ track greater than the range of a proton with the same momentum) as a function of momentum (combined ν -Ne and $\bar{\nu}$ -Ne data). The fitted curves show the parameterisations used for the efficiencies.

Figure 2 Invariant p^2 distributions of the backward particles, combined ν and $\bar{\nu}$ data. (a) All neon and deuterium backward proton data, also neon data with only one proton, (b) π^+ , (c) π^- . The fitted lines are discussed in section 4 (slopes in table 2).

Figure 3 Slope parameter, B, as a function of $\cos\theta$ for proton momenta between 350 and 800 MeV/c (combined ν and $\bar{\nu}$ data).

Figure 4 Slope parameter, B, for backward protons in neon as a function of the hadron shower energy, for proton momenta between 350 and 800 MeV/c (combined ν and $\bar{\nu}$ data).

Figure 5 Average multiplicity of backward protons versus the number of forward protons.

Figure 6 v_N versus α for neon and deuterium, (a) $\nu - Ne$, (b) $\nu - Ne$ events with only one proton and $\nu - D_2$, (c) $\bar{\nu} - Ne$, (d) $\bar{\nu} - Ne$ events with only one proton and $\bar{\nu} - D_2$. The lines show the prediction of the two-nucleon correlation model.

Figure 7 Ratio N_{π^-}/N_{π^+} for events with backward protons, slow forward protons and without detected protons as a function of pion momentum. (a) $\nu - Ne$, the curve represents the variation of the pion absorption cross section in deuterium for $\pi^+d \rightarrow pp$ used in reference 14b, (b) $\bar{\nu} - Ne$.

Figure 8 $\langle y_{vis} \rangle_{Bp}$ versus α for neon events with only one proton and for deuterium, (a) ν , and (b) $\bar{\nu}$.

Identification Efficiency

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8