NEUTRINO INTERACTIONS, PROTON PRODUCTION AND A NUCLEAR EFFECT

BEBC Collaboration

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ABSTRACT

Neutrino interactions are classified by the presence or absence of protons with momentum below 600 MeV/c at the interaction vertex. Interactions producing protons have softer x distributions for hydrogen and deuterium targets as well as for neon. In contrast to a recent claim, the effect is therefore not directly related to any nuclear effect in neon.

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A new tool has been proposed for investigating the EMC effect in leptonic interactions^[1]. It was shown that neutrino interactions on freon producing slow protons had a softer x distribution than those without. This led to the suggestion that the events with slow secondary protons had taken place on deeply bound nucleons and consequently showed an ‘undiluted nuclear effect’. The changes in the shape of the x distribution (EMC effect) have been studied in several experiments by comparing lepton scattering off light and heavy nuclei. The potentially very interesting new idea^[1] is that one might instead compare interactions on tightly-bound and quasi-free nucleons using data from one target: the interactions with tightly bound targets in the centre of the nucleus would have extra slow protons while those on quasi-free nucleons would not.

We have investigated this suggestion using charged current (CC) interactions from the Big European Bubble Chamber exposed to the CERN SPS wide band neutrino and antineutrino beams. We have used data taken in the same experimental conditions on neon, deuterium and hydrogen targets - these data have been compared in detail previously^[2,3]. The interactions were required to have a secondary muon identified by the external muon tracking chambers, with momentum above 5 GeV/c. Table 1 summarises the data used.

The procedure is simply to select CC events producing slow protons and see if their kinematical distributions differ from those of the rest of the CC events.

In neon the slow protons stop, giving characteristic tracks which distinguish them from pions, while slow protons in deuterium and hydrogen are identified by their range or ionisation. The identified protons from reference 1 were any ‘dark’ tracks: some 49% of the neutrino interactions had dark tracks, which had a mean momentum of 340 MeV/c. Here we only use protons with momentum below 600 MeV/c, both to have a uniform sample of protons detected with good efficiency from the three targets and also to be directly comparable to reference 1. The deuterium and hydrogen data include measurements for protons with momenta down to 150 MeV/c. For the neon, protons were measured only above 350 MeV/c, but the presence of stubs (i.e. protons with momentum below 350 MeV/c and above about 180 MeV/c) was recorded. With these selections, it can be seen from table 1 that 51% of the ν - Ne interactions have a visible proton. This is essentially the same fraction as had ‘dark’ tracks in reference 1.

As usual we estimate the neutrino energy, E_ν , from the measured muon and hadron shower momentum, $\vec{P}^{h,vis}$. The estimated neutrino energy includes a correction for unseen neutrals computed by imposing transverse momentum balance, using

$$E_\nu = P_L^\mu + P_L^{h,vis} (P_T^\mu / P_T^{h,vis})$$

(as in reference 1) before the calculation of the kinematic quantities: P_L is the longitudinal momentum and P_T the transverse momentum (in the neutrino-muon plane) relative to the neutrino direction. In order to ensure the neon data were as similar as possible to the hydrogen and deuterium data, only the charged particles were used to measure $\vec{P}^{h,vis}$ (thus gamma conversions and neutral secondary reinteractions were ignored for all events). This procedure, which was checked in the previous comparisons of the same experiments, enables about the same fraction of the hadron shower momentum to be measured in neutrino interactions on neon as in neutrino interactions on hydrogen and deuterium. In this way the experimental smearing of the distributions of kinematical variables, such as x , is very similar in all these data samples. Nevertheless, in this analysis we disregard the region with x above 0.6 where the smearing effects for each data sample are large. This large x region is not directly relevant to the shape of the distribution at small x , although it does affect the overall normalisation. Leaving protons with momenta up to 600 MeV/c out of $\vec{P}^{h,vis}$ made only insignificant changes in the x distributions.

Figure 1a shows the ratio, R , of the normalised x distributions for the events with and without dark tracks from reference 1: a slope is observed, reminiscent of the EMC effect. Figure 1b shows R (the ratio of the normalised x distributions for the events with one or more protons below 600 MeV/c to those without) for the ν Ne data: a similar slope is observed as for freon. This is

reasonable since the average A of freon (20.7) is very close to that of neon (20.2). Figure 1c and 1d show the νD_2 data and νH_2 data. The slope seen in 1a and 1b is present for all the neutrino data, is larger for deuterium than for neon, and is greatest for hydrogen (note the changes in scale). The data clearly show that the interactions producing slow protons have a softer x distribution than those without slow protons. However, the fact that the slope is also seen in the H_2 and D_2 data demonstrates that it is not a nuclear effect but a property of the interaction on the nucleon. Thus far the neutrino data completely dismiss the possibility of any nuclear effect producing the slopes.

For completeness the same ratio is shown in figures 1b,c,d for antineutrinos. The slope is again larger for deuterium and greatest for hydrogen.

These results may be qualitatively related by a model whose main feature is that in deuterium and neon there are additional sources of slow protons which reduce the strong effect (due to protons produced in the primary interaction) seen in hydrogen. Several other factors also play some role, however. First we discuss the effects of the biased selection of neutron and proton targets in deuterium, caused by requiring visible spectator protons.

In deuterium, the interactions on neutrons with a visible spectator proton introduce slopes in R because the neutron and proton structure functions differ. The νD_2 interactions on the two valence d quarks in the neutron have a harder x distribution than those on the valence d quark in the proton. Thus the neutron-target events selected by the presence of a visible spectator proton will have a harder x distribution than the remaining (neutron + proton) events. This produces a rise in R for νD_2 in figure 1c, indicated by the curve labelled *a* (estimated from the deuterium data[†]). This rise is not seen because the contribution of proton events showing a sharp decrease in R (the hydrogen-like effect, as in figure 1d) is much larger. Conversely, the $\bar{\nu} D_2$ interactions on the valence u quark in the neutron have a softer x distribution than those on the two valence u quarks in the proton, and the neutron-target events with a visible spectator will have a softer x distribution than the events without. This decrease in R for $\bar{\nu} D_2$ is indicated by the curve *b* in figure 1c. The decrease is more significant in the data because of the contribution of proton events with the distribution in figure 1d. Overall, the effect seen in deuterium is not explained by the difference of proton and neutron structure functions alone, but is mainly a dilution of the pronounced effect seen in hydrogen by the addition of neutron-target events.

In neon the effects are further reduced by the addition of secondary protons from nuclear breakup and intranuclear cascades^[4]. Thus the νNe data have a less pronounced slope than νD_2 and the νD_2 less than the νH_2 , because the sample of H_2 -like events showing the effect is increasingly contaminated by samples with no such effect. To illustrate this, the crosses on figure 1b show a simple calculation of R for neon. In this example R has been estimated by taking the deuterium data with secondary protons, and allowing for the fact (see table 1) that a further 40% of the events without secondary protons in deuterium have additional protons in neon. The crosses indicate the mean of the calculations for neutrino and antineutrino, since their difference is small.

The neon data also includes a coherent diffractive contribution⁽⁵⁾, mostly for x below about 0.1. In coherent interactions in neon the nucleus recoils without breaking up and is not detected, so that coherent events in neon contribute at small x to the denominator of R . However for hydrogen and deuterium the equivalent diffractive interactions will usually have a visible proton and so contribute to the numerator. If the coherent events in neon were moved to the numerator also, this would increase R_{DNe} below $x \sim 0.1$ by about 10%.

Figure 2 shows the ratio of the normalised x distributions for the interactions producing slow protons divided into two classes: those with higher momentum (between 350 and 600 MeV/c) and lower momentum (below 350 MeV/c). The hydrogen data (figures 2e and 2f, note the scale) show a statistically significant difference between the two classes which is not visible in the deuterium

[†] The curves *a* and *b* were estimated by calculating R for (expected interactions on neutrons with a seen spectator) / (rest of the deuterium data). As usual interactions on neutrons (without spectators) are selected by an even number of charged secondaries.

or neon data. In the deuterium data (figures 2c and 2d) the protons below 350 MeV/c are a mixture of spectators and protons equivalent to those observed in hydrogen, so they show a less pronounced increase at small x than in the hydrogen data. In neon (figures 2a and 2b) the low momentum protons are augmented by many stubs usually attributed to nuclear breakup and the higher momentum protons include many produced by nuclear cascades.

It is interesting to consider the mechanisms which give soft x distributions for events in hydrogen producing slow protons, for example proton production from interactions on sea and valence quarks^[6], or diffractive interactions. However such an analysis is beyond the scope of this letter; although proton production in deuterium^[7] and backward proton production in the neon data have been analysed in detail^[8].

We also observe that pion reinteractions do appear to supply slow protons, as demonstrated for nuclear cascades in reference 4 but contrary to suggestions in reference 1. Figure 3 shows the mean numbers of protons and stubs as a function of the number of negative secondaries, N_{h-} , in the event (mainly π^-). We choose the negative secondaries as they indicate better the original multiplicity in the neutrino-nucleon interaction, since reinteractions or nuclear cascades increase the mean observed hadronic charge. Not only are more protons produced in neon interactions than in deuterium, but also the numbers of protons and stubs seen in neon increase with the negative multiplicity, as expected for additional production by reinteractions. The correlated increases in negative multiplicity and the number of protons in the event (shown in figure 3) indicate that some $(17 \pm 3)\%$ of the protons in neon between 350 and 600 MeV/c and $(8 \pm 1)\%$ of the protons below 350 MeV/c are associated with the increase.

In conclusion, we have shown that neutrino interactions producing protons with momenta below 600 MeV/c have softer x distributions than events without, but with less softening in deuterium than in hydrogen and less still in neon. This result precludes interpreting the observed^[1] softness of x distributions of interactions producing slow protons in neon and freon as being due to nuclear effects.

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	νNe	νD_2	νH_2	$\bar{\nu}\text{Ne}$	$\bar{\nu}\text{D}_2$	$\bar{\nu}\text{H}_2$
CC events	9520	22196	18669	16536	15071	10788
With $p_{prot} < 600$ MeV/c	51%	16%	10%	46%	13%	8%
With $350 < p_{prot} < 600$ MeV/c	26%	7.5%	7.7%	21%	6.1%	5.7%
With $p_{prot} < 350$ MeV/c	25%	8.5%	2.3%	25%	6.6%	2.5%

Table 1: Summary of data from the experiments used for this analysis.

Figure captions

Figure 1. The ratio, R , of the normalised x distributions for interactions with and without secondary protons, 'p + stub > 0' selects interactions with a secondary proton below 600 MeV/c: (a) ν - freon from reference 1, where n_D is the number of 'dark' tracks seen, (b) ν Ne and $\bar{\nu}$ Ne, the crosses are a simple estimate from D_2 (see text), (c) νD_2 and $\bar{\nu} D_2$ (curves are described in text), (d) νH_2 and $\bar{\nu} H_2$.

Figure 2. The ratio, R , of the normalised x distributions for interactions with and without protons produced, for : (i) protons with higher momentum - between 350 and 600 MeV/c - dark points, (ii) only protons with lower momentum - below 350 MeV/c - light points, (a) ν Ne, (b) $\bar{\nu}$ Ne, (c) νD_2 , (d) $\bar{\nu} D_2$, (e) νH_2 , (f) $\bar{\nu} H_2$.

Figure 3. The mean number of observed protons per event as a function of the number of negative secondaries, N_{h-} , for : (a) protons between 350 and 600 MeV/c, (b) protons below 350 MeV/c.

R R R R

Figure 1

Figure 2

Figure 3