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Intranuclear cascade in ν_μNe interactions

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We report a study of multiplicities in ν_μNe charged-current interactions. The data were obtained at Fermilab, using the wide-band neutrino beam incident on the 15-ft bubble chamber filled with a neon-hydrogen mixture. We measure a mean positive-charge excess of 0.58 ± 0.02, and show that it consists mainly of "grey protons," i.e., protons in the momentum range 0.2 to 1.0 GeV/c. The average number of secondary collisions in the intranuclear cascade is found to be 1.16 ± 0.04. The distribution of the number of grey protons is in good agreement with the model of Andersson, Otterlund, and Stenlund.

INTRODUCTION

There have been many studies[1] of particle production in hadron-nucleus collisions. One source of final-state particles is the process of multiple projectile collisions with the nucleons of the target nucleus. An important goal of many experiments is to determine the number of projectile collisions ν in any event. A common approach is to deduce ν from the number of "grey protons" n_p, i.e., protons with momentum in the range 0.2 to 1.0 GeV/c. (Slower protons, sometimes called black protons, are thought[2] to represent the last stage of evaporation of the nucleus.)

A complication in these analyses is that there is a second source of particles, namely, the collisions of secondary particles as they pass through the nucleus. This intranuclear cascade[3] can also produce grey protons. The difficulty in separating these two sources of final-state particles has recently been reemphasized by DeMarzo *et al.*[4]

In addition to determining the number of projectile collisions, another goal of hadron-nucleus experiments is to understand the nature of the positive-charge excess of relativistic particles.[5] Here again, the two possible sources of particles complicate the issue.

In this paper we present a study of particle production in charged-current neutrino-neon interactions, representing the reaction

$$\nu_\mu+\text{Ne}\rightarrow\mu^-+\text{hadrons}\ . \qquad (1)$$

A notable feature of this reaction is that there is only one projectile collision, since the muon does not reinteract in the nucleus. The final-state hadronic system reflects only the intranuclear cascade and thereby eases the interpretation of the process. It should be noted, however, that most hadron-nucleus experiments are carried out at fixed incident-beam energies, whereas in our experiment the incident neutrino ranges in energy from 0 to 200 GeV. The hadronic system in our experiment has an effective mass ranging from about 2 to 10 GeV/c^2, with an average of 5 GeV/c^2.

The data were obtained using the Fermilab horn-focused wide-band neutrino beam incident on the 15-ft bubble chamber filled with a 62% (atomic) neon-hydrogen mixture. The chamber was in a 30-kG magnetic field, allowing momentum measurement and charge identification of all tracks. The liquid had an interaction length of 125 cm, so that hadrons usually interacted or stopped within the chamber, while muons left the chamber without interacting. This provided a clean way of isolating reaction (1): events with a negative leaving track were identified as charged-current events. (If there was more than one such track in an event, the fastest was taken to be the μ^-.) The only significant background was that due to pion punchthrough in neutral-current events, i.e., if a π^- were to leave the chamber without interacting, it would fake a μ^-. To reduce this background, all muons were required to have momentum greater than 2 GeV/c and to have at least 70 cm of potential path length in the chamber. After these cuts, our final sample consisted of 3690 charged-current events, whose average energy was about 50 GeV. The punchthrough background was 9.9%, and the results presented in this paper are corrected for this background. Details of the background subtraction are given in the Appendix; here we note only that the background subtraction had a negligible effect on the results presented.

POSITIVE-CHARGE EXCESS

Table I shows the mean values of the total charge multiplicity $n_{\rm ch}$, the positive multiplicity n_+, negative multiplicity n_-, and net charge $(n_+ - n_-)$. Protons in the momentum range 0.2 to 1.0 GeV/*c*, i.e., the so-called grey protons, usually stop within the bubble chamber and can be readily identified from their range-momentum correlation. Table I also shows the mean number of grey protons, n_p, and the mean momenta of protons, π^+ and π^-. About 2% of the tracks failed in the geometrical reconstruction, and therefore could not be used for the determination of mean momenta. However, the multiplicities were unaffected, because the sign of charge of all tracks had been determined by visual inspection of the film at the time the events were measured. A check of a sample of failing tracks indicated that the sign of charge was correctly set by the measurer. The first observation we make from Table I is that the mean net charge of 0.92±0.02 indicates a positive charge excess. In neon we have an equal number of protons and neutrons. However, charged-current neutrino interactions occur twice as often on neutrons as on protons, because the *d* quark is the only valence quark that can participate in the interaction. This simple prediction is modified because of sea quarks, and a weighted world average for the neutron to proton cross section ratio[6] is 1.96±0.07. This is very close to a theoretical prediction of 1.95 which can be derived from the quark structure functions obtained by Field and Feynman[7] using electroproduction data. If we use the experimental average value of 1.96±0.07, we would expect a mean net charge (in the absence of an intranuclear cascade) of

$$\langle Q \rangle_{\rm no\ cascade} = 0.34 \pm 0.01 \; .$$

We conclude that the cascade in ν_μ Ne interactions produces a mean positive-charge excess of 0.58±0.02.

We investigate next what the properties are of this charge excess. To identify its composition, we need to isolate a subsample of events in which no secondary collisions take place. Events with net charge +1 could represent νp reactions, or νn reactions where secondary collisions increased the charge of the final state. On the other hand, events with net charge 0 are likely to represent a fairly pure sample of νn interactions with no extra collisions. In Table I we show the mean multiplicities for this subsample, consisting of 1237 events out of the total sample of 3690. We note that the mean grey-proton multiplicity is 0.17±0.01 compared to 0.57±0.02 for all events. We need to estimate also the grey-proton production in νp reactions with no secondary collisions. To make this estimate, we note first that in our νn control sample the mean grey-proton multiplicity of 0.17 is about 7% of the mean positive-charge multiplicity of 2.40. Previous experiments have found that νp reactions in hydrogen[8] have charge multiplicities greater than those of νn reactions in deuterium[9] by about 0.3. We therefore estimate that the mean grey-proton multiplicity in νp collisions is about 7% of 2.7, or 0.19. Then in our experiment in neon, with a νn cross section twice as great as νp, we estimate that when there are no secondary collisions the mean grey-proton multiplicity is 0.18±0.02 compared to 0.57±0.02 for all events. The difference of 0.39±0.04 represents the observed mean proton excess due to secondary collisions. The error on the difference includes the uncertainty due to the fact that our control sample of events with net charge 0 is not a completely pure sample of events with no extra collisions.

The true proton excess is greater than the observed value of 0.39 derived from the table. Protons are identified only if they stop in the chamber; all interacting tracks are called pions. By using the known momentum-dependent interaction length in the liquid, we calculate that in addition to the stopping protons another (24±4)% would have interacted before they stopped. Still another source of loss is that protons could *leave* the chamber. Using a Monte Carlo program to generate event vertices randomly in the fiducial volume, we calculate that an extra 3% of our protons would have left the chamber before they stopped. Applying both corrections, the proton excess of 0.39 rises to 0.50±0.05, and the corrected mean proton momentum becomes 0.460 GeV/*c*. We conclude that our overall mean positive-charge excess of 0.58±0.02 mainly consists of grey protons.

DeMarzo *et al.*[4] have pointed out that a secondary hadron collision off a proton would produce a charge excess of +1, while a collision off a neutron would produce no excess. We have equal numbers of protons and neutrons in neon, so the charge excess is just half the number of extra collisions. So our mean positive charge excess of 0.58±0.02 implies that the average number of secondary

TABLE I. Mean multiplicities in charged-current ν_μ Ne interactions.

	All events	Events with zero net charge
$\langle n_{\rm ch} \rangle$	5.76 ±0.05	4.79±0.07
$\langle n_+ \rangle$	3.34 ±0.03	2.40±0.03
$\langle n_- \rangle$	2.43 ±0.02	2.40±0.03
$\langle n_+ - n_- \rangle$	0.92 ±0.02	0
$\langle n_p \rangle$	0.57 ±0.02	0.17±0.01
$\langle p_p \rangle$ (GeV/*c*)	0.450±0.004	0.52±0.01
$\langle p_{\pi^+} \rangle$ (GeV/*c*)	2.23 ±0.03	2.62±0.06
$\langle p_{\pi^-} \rangle$ (GeV/*c*)	2.22 ±0.04	2.25±0.07

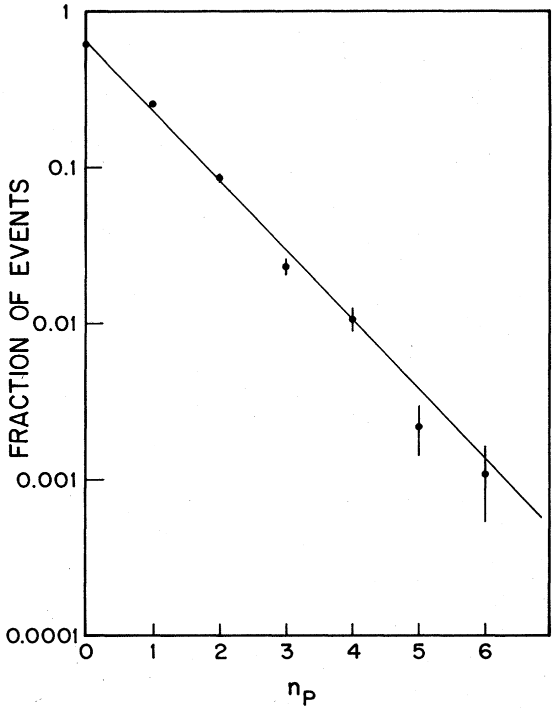

FIG. 1. The fraction of events with n_p grey protons, i.e., stopping protons in the momentum range 0.2 to 1.0 GeV/c. The solid line is the prediction of the model by Andersson, Otterlund, and Stenlund for one projectile collision.

collisions in the intranuclear cascade is 1.16 ± 0.04, over and above the original neutrino interaction.

GREY-PROTON PRODUCTION

Hadron-nucleus experiments often attempt to deduce the number of projectile collisions from the distribution of grey protons. One of the most frequently used models is that of Andersson, Otterlund, and Stenlund.[10] This model makes a particularly simple prediction for the limiting case of one projectile collision, namely, that the fraction of events with n_p grey protons is

$$P(n_p)=(1-x)x^{n_p} ,$$

where

$$x=\langle n_p\rangle/(1+\langle n_p\rangle) .$$

(Note that the prediction is absolute, already normalized.) In hadron-nucleus experiments it is necessary to make assumptions in order to isolate events with only one projectile collision. In our ν_μ Ne data, as discussed above, all the events have only one projectile collision. Figure 1 displays the distribution of the fraction of events with n_p grey protons and the solid line is the prediction of the model.[10] The agreement is quite good.

In the preceding section we noted that the mean positive-charge excess consisted mostly of grey protons on the average. We can now examine this suggestion more carefully by plotting the mean charge excess as a function of number of grey protons. The mean charge excess is

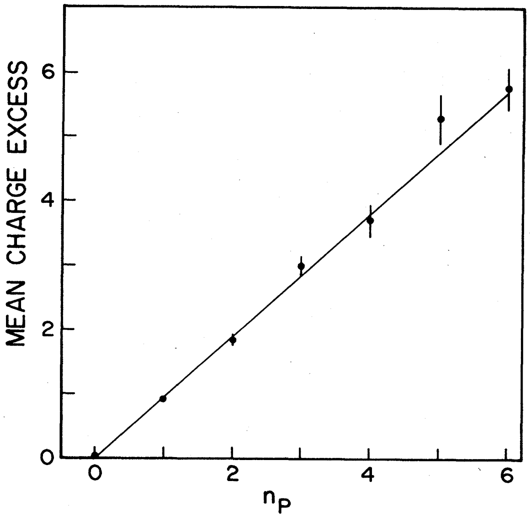

FIG. 2. The mean positive-charge excess as a function of number of grey protons. The charge excess is the observed charge less the expected charge of 0.34 for no intranuclear cascade. The solid line is a linear fit to the data.

$$\langle Q\rangle_{\text{excess}}=\langle Q\rangle_{\text{observed}}-\langle Q\rangle_{\text{no cascade}} ,$$

where

$$\langle Q\rangle_{\text{no cascade}}=0.34 .$$

In Fig. 2 we show $\langle Q\rangle_{\text{excess}}$ vs n_p. The straight line is a linear fit to the data, with a χ^2 of 4.7 for 5 degrees of freedom. The slope is 0.95 ± 0.02. The closeness of the slope to 1.0 is a clear indication that the charge excess arises mostly from grey protons.

Finally, as mentioned in the preceding section, the number of secondary collisions is just twice the charge excess. So Fig. 2 implies that on the average the number of secondary collisions is twice the number of grey protons.

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APPENDIX

The punchthrough background in the charged-current sample consists of neutral-current events in which a π^- (over 2 GeV/c) leaves the bubble chamber without interacting, thereby satisfying the μ^- definition. We can calculate this background by counting the numbers of positively charged leaving (L^+) and interacting (I^+) tracks over 2 GeV/c in the combined sample of charged and neutral current events. Since the positive tracks are all hadrons, the L^+/I^+ ratio is a measure of the punchthrough probability. Multiplying the ratio by the number of negative interacting tracks (I^-) over 2 GeV/c in the combined sample yields the expected number of punchthrough tracks. In this way we found that the background in the charged-current sample is $(9.9\pm0.6)\%$.

To correct any charged-current distribution for the presence of this background, we make use of our neutral-current sample. The fastest negative interacting track is taken to represent the fake muon, and the corresponding distribution is plotted. The distribution is normalized to 9.9% of the charged-current distribution and then subtracted from it. For the work presented in this paper, the background subtraction was essentially negligible, much less than a standard deviation.

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[1] W. Busza, Acta Phys. Pol. **B8**, 333 (1977), and references therein; C. D. Rees *et al.*, Z. Phys. C **17**, 95 (1983); W. M. Yaeger *et al.*, Phys. Rev. D **16**, 1294 (1977).

[2] M. K. Hegab and J. Hufner, Nucl. Phys. **A384**, 353 (1982).

[3] A. Dar and I. Vary, Phys. Rev. D **6**, 2412 (1972).

[4] C. DeMarzo *et al.*, Phys. Rev. D **29**, 2476 (1984).

[5] D. H. Brick *et al.*, Nucl. Phys. **B201**, 189 (1982), and references therein; W. D. Shepard *et al.*, in *Multiparticle Dynamics 1983,* proceedings of the XIV International Symposium, Lake Tahoe, edited by J. F. Gunion and P. Yager (World Scientific, Singapore, 1983), p. 954.

[6] The weighted world average was computed using values given by G. Snow, in *Neutrino '81,* proceedings of the International Conference on Neutrino Physics and Astrophysics, Maui, Hawaii, edited by R. J. Cence, E. Ma, and A. Roberts (University of Hawaii High Energy Physics Group, Honolulu, 1981), p. 427.

[7] R. D. Field and R. P. Feynman, Phys. Rev. D **15**, 2590 (1977).

[8] P. Allen *et al.*, Nucl. Phys. **B181**, 385 (1981).

[9] D. Zieminska *et al.*, Phys. Rev. D **27**, 47 (1983).

[10] B. Andersson, I. Otterlund, and E. Stenlund, Phys. Lett. **73B**, 343 (1978).