Production of cumulative protons in an interaction of neutrinos with emulsion nuclei

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A cumulative effect in the interactions of neutrinos in the energy range 10–200 GeV with emulsion nuclei has been studied. For the first time, a decrease in the average yield of cumulative protons has been observed at a neutrino energy above 50 GeV [the square 4-momentum was above 15 $(\text{GeV}/c)^2$, and the energy transfer was above 20 GeV].

The cumulative effect which is observed in the interaction of hadrons with nuclei[1,2] has attracted much interest in the production of particles whose production at a free nucleon is forbidden by the reaction kinematics. At present, the phenomenon of nuclear scaling has been studied least in neutrino interactions. Limited experimental data are available on the interaction of neutrinos with light nuclei ($\langle A \rangle = 20, 30$).[3,4] It is accordingly very important to carry out experiments with photographic emulsions, which make possible a detailed study of each neutrino interaction with a heavy nucleus ($\langle A \rangle = 80$).

We have studied the production of cumulative protons at emulsion nuclei as part of experiment *E*-564 during bombardment of a nuclear emulsion in a neutrino beam at energies of 10–200 GeV at the Fermi National Accelerator Laboratory. The experimental procedure and the methods for determining the neutrino energy are described in Ref. 5.

We selected 151 interactions with a charged current. In order to distinguish cumulative protons, we developed a method for determining the momentum of the *g*-particles from measurements of their relative ionization in the emulsion.[6] We selected events in which protons were emitted backward in the laboratory frame of reference

TABLE I.

N_{cp}	$\langle N_b \rangle$	$\langle N_g \rangle$	$\langle N_{gfor} \rangle$	$\langle N_s \rangle$
0	4.4 ± 0.2 [1)]	1.4 ± 0.1	1.4 ± 0.1	7.0 ± 0.3
1	5.4 ± 0.6	3.0 ± 0.3	2.0 ± 0.3	6.5 ± 0.5
⩾ 2	10.0 ± 1.0	5.6 ± 0.5	3.1 ± 0.6	7.4 ± 0.6

[1)]All the errors are statistical.

with momenta exceeding 300 MeV/c. In 31 ν interactions, i.e., $20.5 \pm 2.7\%$ of the total number of events, we observed cumulative particles. We detected a total of 50 cumulative protons, so their average relative yield is $\langle N_{cp} \rangle = 0.33 \pm 0.07$.

We have previously published results of a study of the cumulative effect: the distribution of the cumulative protons in the square of the 4-momentum, in the kinetic energy, in the emission angle, and in the scaling variables.[7] We have also carried out an analysis of the A dependence of the yield of cumulative protons. The use of a nuclear emulsion as target makes it possible to bring out the correlation between the number of cumulative protons and the multiplicities of b, g, and s particles in the emulsion—information of importance for identifying the mechanism for the multiple production of cumulative particles. This problem is particularly interesting for neutrino events, since a neutrino definitely interacts only once in a nucleus.

Table I shows the average multiplicities for events without cumulative particles ($N_{cp} = 0$), with one such particle ($N_{cp} = 1$), and with two or more ($N_{cp} \geqslant 2$). Here $\langle N_b \rangle$, $\langle N_g \rangle$, and $\langle N_s \rangle$ are the average multiplicities of the b, g, and s tracks, and $\langle N_{gfor} \rangle$ is the average multiplicity of the forward-emitted g tracks. We see that the average multiplicity of the relativistic particles ($\langle N_s \rangle$) does not depend on the presence or number of cumulative protons and that the average multiplicities of the b and g particles are proportional to N_{cp}.

In a study of the interaction of high-energy particles with nuclei, a point of major interest is determining the space-time picture of the interaction.[8] The use of heavy nuclear targets in beams of high-energy neutrinos makes it possible, in particular, to test the hypothesis that the hadron production length is finite.[8,9] As we know, the

TABLE II.

E_ν, GeV	$\langle N_{cp} \rangle$	Q^2(GeV/c)^2	
		with cp's	without cp's
10 – 30	0.56 ± 0.14	6.2 ± 1.5	5.4 ± 0.7
30 – 50	0.45 ± 0.13	15.9 ± 2.3	9.4 ± 1.3
50 – 200	0.10 ± 0.04	13.6 ± 3.4	22.4 ± 2.3

TABLE III.

Q^2(GeV/c)^2	$\langle N_{cp} \rangle$
0 - 10	0.40 ± 0.07
10 - 15	0.53 ± 0.13
> 15	0.10 ± 0.07

multiplicity of g particles is a parameter which characterizes the number of intranuclear interactions, and the proportionality of the yield of cumulative protons to the quantity $\langle N_g \rangle$ means that we can use $\langle N_{cp} \rangle$ as a characteristic of the development of an internuclear cascade.

Table II shows $\langle N_{cp} \rangle$ and the square of the 4-momentum, Q^2, versus the neutrino energy E_ν for events without and with cumulative protons. We see from this table that in the interval 10 GeV$\leqslant E_\nu \leqslant$30 GeV the value of $\langle Q^2 \rangle$ does not depend on whether there are cumulative protons in the event; in the interval 30–50 GeV the value of $\langle Q^2 \rangle$ is larger for events with cumulative protons than for events without them; and at $E_n > 50$ GeV the value of $\langle Q^2 \rangle$ in events with cumulative protons is smaller than that in events without them.

Table III shows the results of a sorting of the events into three Q^2 intervals with roughly the same statistical bases.

It can be seen from Tables II and III that at $E_\nu > 50$ GeV and $Q^2 > 15$ (GeV/c)^2 the average yield of cumulative protons falls off sharply, to a value $\langle N_c \rangle = 0.10 \pm 0.04$. The following conclusion can be drawn from these results: As E_ν (or Q) is increased, the momentum transferred to the parton jet increases, and the contribution of the secondary interactions of hadrons decreases, in agreement with the hypothesis of a finite hadron production length. It is possible that at sufficiently large values of the momentum transfer the hadrons are produced outside the nucleus, so the contribution of secondary interactions dies out.

[1]A. M. Baldin, Kratk. Soobshch. Fiz. No. 1, 1971, p. 35.
[2]A. M. Baldin *et al.*, Yad. Fiz. **18**, 79 (1973) [Sov. J. Nucl. Phys. **18**, 41 (1973)].
[3]V. I. Efremenko *et al.*, Phys. Lett. **B84**, 511 (1979).
[4]A. A. Ivanilov, V. I. Konyushko, V. M. Korablev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 390 (1979) [JETP Lett. **30**, 362 (1979)].
[5]Smart *et al.*, Acta. Phys. Polon. **B17**, 1, 41 (1986).
[6]V. M. Rappoport *et al.*, Preprint No. 159, P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1987.
[7]R. Ammar *et al.*, Preprint No. 48, FIAN, 1988.
[8]N. N. Nikolaev, Usp. Fiz. Nauk **134**, 369 (1981) [Sov. Phys. Usp. **24**, 531 (1981)].
[9]E. V. Kancheli, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 465 (1973) [JETP Lett. **18**, 274 (1973)].
[10]M. I. Adamovich *et al.*, in: Proceedings of the Lebedev Physics Institute, Vol. 108, Plenum, New York; Y. A. Abdurazakova *et al.*, Acta Phys. Polon. **B18**, 249 (1987).

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