Nuclear effects in high-energy antineutrino interactions

V. I. Efremenko, A. V. Fedotov, P. A. Gorichev, V. S. Kaftanov, G. K. Kliger, V. Z. Kolganov, S. P. Krutchinin, M. A. Kubantsev, I. V. Makhlyueva, M. M. Savitsky, V. I. Shekeljan, and V. G. Shevchenko
Institute of Theoretical and Experimental Physics, Moscow, Union of Soviet Socialist Republic

J. P. Berge, D. Bogert, R. Endorf,* R. Hanft, J. Malko, G. Moffatt,* F. A. Nezrick, R. Orava, W. Smart, and J. Wolfson
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

V. V. Ammosov, A. G. Denisov, G. S. Gapienko, V. A. Gapienko, V. I. Klyukhin, V. I. Koreshev, P. V. Pitukhin, E. A. Slobodyuk, V. I. Sirotenko, A. A. Volkov, and V. G. Zaets
Institute of High Energy Physics, Serpukhov, Union of Soviet Socialist Republic

J. Bell, C. T. Coffin, W. Louis, B. P. Roe, R. T. Ross, A. A. Seidl, D. Sinclair, and E. Wang
University of Michigan, Ann Arbor, Michigan 48109
(Received 11 February 1980)

Backward protons from neutrino and antineutrino interactions in a Ne-H_2 mixture are studied. The inclusive characteristics of the reactions are presented for both neutral- and charged-current events and comparison with models are made. The data are in agreement with the hypothesis of nuclear scaling.

I. INTRODUCTION

A large number of experiments of the type

$$h(\gamma)+A\to(\pi^{\pm},p,d,\ldots,)+X$$

have been performed to study the collective behavior of the nucleons in the nuclear target (A).[1] In these experiments the final-state particle ($\pi^{\pm},p,d\ldots$) travels backward relative to the beam direction in the laboratory system. Since the observed backward protons cannot originate from interactions on free stationary nucleons, they indicate the presence of nuclear effects in the scattering process.

The inclusive spectrum of backward protons can be parametrized with an exponential

$$\frac{E}{p}\frac{d\sigma}{dp^2}=C\exp(-Bp^2), \quad (1)$$

where E and p are the energy and momentum of the proton in the laboratory system. The slope (B) does not depend on the energy of the primary particle and is insensitive to the mass of the target nucleus. The absolute scale (C) depends only weakly on the incident energy. These experimental findings have led to the hypothesis of nuclear scaling.[1] It has been suggested that reactions of this type provide direct information on the high-momentum part of the nuclear wave function.[2-4]

II. MODELS

In a model based on short-range correlations among the nucleons [short-range order (SRO)] the backward protons are viewed as manifestations of two-, three-, or four-nucleon clusters which have high relative momenta inside the target nuclei.[2] In the kinematical domain available for our analysis, two-nucleon clusters should dominate. In this model the incident neutrino interacts with a nucleon which has its momentum vector oriented in the forward direction. The neighboring spectator nucleon is then thought to travel in the opposite (backward) direction. The SRO model predicts smaller average Bjorken x (Ref. 5) for these events due to smaller available center-of-mass energy of the interaction (similar to a Doppler effect), i.e.,

$$x=x'(2-\alpha), \quad (2)$$

where x' is the corresponding x value for an interaction on a stationary free nucleon, and $\alpha=(E_p-p_{\parallel})/m$ with E_p, m, and $p_{\parallel}$ the proton energy, mass, and longitudinal momentum with respect to the neutrino direction.

A second model assumes an initial "prepared" state of the nucleus with a fast backward nucleon whose momentum is balanced by the rest of the nucleons.[3,4] Deep-inelastic scattering then occurs off the fast backward-oriented nucleon with a momentum transfer that is so small that the struck nucleon does not change its orientation but emerges into the backward hemisphere in the laboratory system. This picture leads to a substantially smaller average x, Q^2, and charged multiplicity for these events as compared to the overall data sample.

A similar model of the target nucleus is adopted in Ref. 6, but in this case the interaction is thought to proceed off the bulk of the nucleus which balances the momentum of a fast single nucleon. This picture does not assign any specific features to the events with backward protons.

Finally, in the multiple-rescattering model, backward protons are thought to result from several successive rescattering processes of a nucleon in this nucleus.[7] No significant effects in the x or Q^2 are foreseen.

III. EXPERIMENTAL DETAILS

In this paper we present the results of a detailed study of nuclear effects in neutrino- and antineutrino-neon interactions. The data comes from a 155 000-picture exposure of the Fermilab 15-ft bubble chamber filled with a heavy Ne-H_2 mixture (64 atomic % Ne). The chamber was exposed to a wide-band antineutrino beam from 400-GeV/c incident protons. A comparison with neutrino events is permitted by the inclusion of the sample of ν-Ne charged-current (CC) interactions recorded as a background in the same experiment. Further experimental details are given in Ref. 8. The present analysis represents an upgraded investigation of the subject originally reported in Ref. 8 based upon a fivefold increase in the sample size. The improved statistics also enable us to study nuclear effects in neutral-current interactions. The neutral-current event sample consists of events in which the fastest charged track does not leave the chamber and for which no muon candidate is found by the external muon identifier. The charged-current contamination in this sample is estimated to be less than 30% which is adequate for the purpose of the following analysis. The neutral-current event-selection procedure does not allow us to distinguish between neutrino and antineutrino induced neutral-current (NC) events. For each of the three data samples, $\bar{\nu}\mathrm{Ne}\to\mu^+X$, $\nu\mathrm{Ne}\to\mu^-X$, $\bar{\nu}(\nu)\mathrm{Ne}\to\bar{\nu}(\nu)+X$, we identify an event as a backward-proton (BP) event [two-backward-protons (2BP) event] if there is one track [two tracks] emerging backward in the laboratory and stopping in the chamber with neither a decay nor interaction and having a momentum in the range 0.2 to 0.8 GeV/c. We found only three events with three backward protons and they have been treated as 2BP events. We made corrections for protons which interact and are misidentified as π^+'s. These corrections result in ~10% growth of relative yields and a small decrease (smaller than statistical errors) of fitted slope parameter B in (1).

TABLE I. Total numbers of events and relative yields.

	Charged current antineutrino	Charged current neutrino	Neutral current
Total sample	4053	611	1018
BP+2BP events	402	73	106
2BP events	52	11	10
(BP+2BP)/Total	0.10 ± 0.01	0.12 ± 0.04	0.10 ± 0.01
2BP/(BP+2BP)	0.13 ± 0.02	0.15 ± 0.05	0.09 ± 0.03

IV. RESULTS

The total numbers of events and relative yields are summarized in Table I (corrected values are given). Within our statistics the yields are equal for all three samples. Invariant proton spectra were fitted according to Eq. (1). The 2BP events entered the distributions twice. Results for the three samples are shown in Figs. 1(a)–1(c). We obtain the following slope parameters (for the momentum interval $0.3<p<0.7$ GeV/c):

$$B(\mathrm{CC},\ \mu^+)=10.7\pm0.7\,,$$

$$B(\mathrm{CC},\ \mu^-)=10.4\pm1.8\,,$$

$$B(\mathrm{NC})=10.5\pm1.6\,.$$

These values are all consistent and are in good agreement with our earlier data published in Ref. 8. They also fit well into the nuclear-scaling hypothesis (see comparison with hadronic data in Ref. 8).

The azimuthal angular distributions (not shown) are consistent with being isotropic. The distributions in $\cos\theta_p$ (θ_p is the angle between the proton momentum vector and the neutrino beam direction) are shown in Fig. 2. As the proton momentum increases a sharp anisotropy occurs in the $\cos\theta_p$ distributions.

Mean values of the total charge $\langle c\rangle$, total multi-

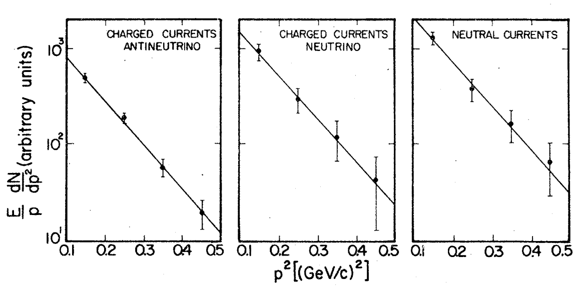

FIG. 1. Inclusive spectra of the backward protons for charged-current antineutrino (a), neutrino (b), and for neutral-current events (c). Solid line is a fit to formula (1) (see the text).

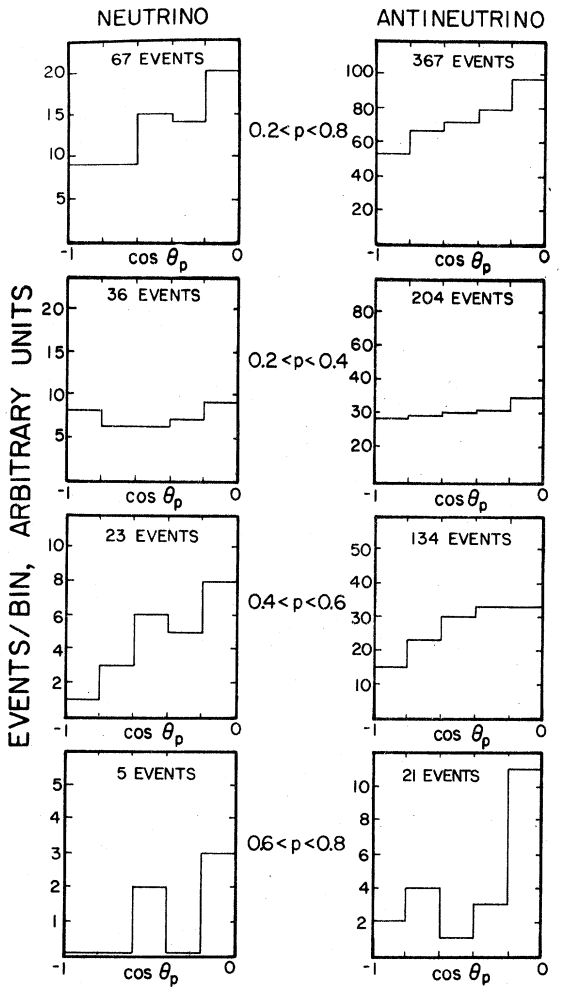

FIG. 2. Distributions in $\cos\theta_p$ for the antineutrino and neutrino BP events. The distributions are given for the entire BP samples (two uppermost) and for three intervals of the proton momenta.

plicity $\langle n\rangle$, and $\langle Q^2\rangle$ for events with backward proton(s) and for the rest of the charged-current neutrino and antineutrino samples are compared in Table II. We also show mean values of v [$v=E_\mu(1-\cos\theta_\mu)/m$, where E_μ and θ_μ are the muon energy and angle]. As seen from Table II for both the ν and the $\bar{\nu}$ samples there is a significant difference in $\langle n\rangle$ and $\langle c\rangle$ between the samples with backward proton(s) and without it. This difference partially follows from the definition of the BP samples.

In the framework of the pair-correlation mechanism[2] it is predicted that

$$\langle y\rangle_\alpha=\langle y\rangle,\quad \langle v\rangle_\alpha=(2-\alpha)\langle v\rangle \tag{3}$$

for $1.3\lesssim\alpha<2$ where $\langle y\rangle$ and $\langle v\rangle$ are mean values for the charged-current sample and $\langle y\rangle_\alpha$ and $\langle v\rangle_\alpha$ are mean y and v for BP events with given value of α.

Figures 3(a) and 3(b) show the results of a comparison of the $\langle v\rangle_\alpha$ and $\langle y\rangle_\alpha$ dependences in α for BP events[9] with a prediction of the pair-correlation scheme[2] obtained using Eq. (3) and the total sample of the antineutrino charged-current events (solid line).

Figures 4(a) and 4(b) illustrate the analysis of correlations between the two protons in 2BP events. For this purpose we compared the distributions in the invariant mass of the two protons M_{pp} and $\cos\theta_{pp}$ (where θ_{pp} is the angle between protons) with similar distributions for two proton tracks taken from independent BP events (which are therefore uncorrelated). There is no apparent correlation. The absence of an enhancement near $\theta_{pp}=90°$ [Fig. 4(b)] does not support the picture in which one backward proton elastically scatters another proton out of the nucleus.

V. CONCLUSION

We have studied samples of ν- and $\bar{\nu}$-induced events, which contain protons in the kinematical region forbidden for interactions off stationary free nucleons. Inclusive properties of these events were investigated for neutrino and antineutrino charged-current samples and for the neutral-current sample. A qualitative check of the pair-correlation model was performed and an agreement with the data was found. A correlation analysis of events with two backward protons was made.

TABLE II. Comparison of events with backward proton(s) with the rest of the charged-current samples.

Variable	$(BP+2BP)_{\bar{\nu}}$	$(CC-BP-2BP)_{\bar{\nu}}$	$(BP+2BP)_\nu$	$(CC-BP-2BP)_\nu$
$\langle c\rangle$	2.9 ± 0.1	1.2 ± 0.1	2.0 ± 0.2	0.7 ± 0.1
$\langle n\rangle$	8.7 ± 0.2	7.3 ± 0.1	11.1 ± 0.6	9.0 ± 0.2
$\langle Q^2\rangle$	3.4 ± 0.3	4.2 ± 0.1	8.2 ± 0.5	8.7 ± 0.3
$10^{-3}\langle v\rangle$	59 ± 3	74 ± 1	85 ± 8	90 ± 3

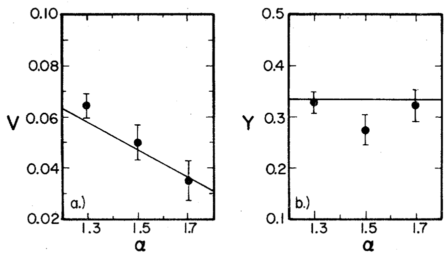

FIG. 3. Comparison of this experiment with predictions of the pair-correlation model (Ref. 2). Solid lines correspond to α dependence of the scaling variables v and y given in Ref. 2.

A comparison of the deep-inelastic features of the events with backward proton(s) and the entire charged-current sample is presented. Although this information cannot provide a stringent test of all the models discussed above, it should stimulate further experimental and theoretical efforts in the field.

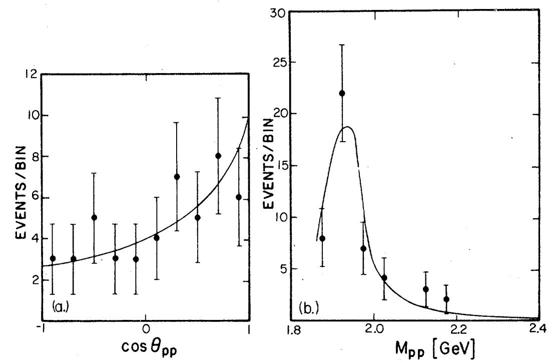

FIG. 4. Analysis of correlations between the two protons in the 2BP events: (a) distribution in $\cos\theta_{pp}$ where θ_{pp} is the angle between the protons, (b) invariant-mass M_{pp} distributions for pairs of protons in the 2BP events. Solid lines are hand-drawn fits to similar distributions of uncorrelated protons belonging to different events.

ACKNOWLEDGMENT

This work was supported in part by the United States Department of Energy and the National Science Foundation.

*Visitor from University of Cincinnati, Cincinnati, Ohio 45221.

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[9]Figures 3 and 4 are plotted for the BP and 2BP events in the antineutrino charged-current sample which is the only one having sufficient statistics for such an analysis.