Cross Sections and Scaling-Variable Distributions of Neutral- and Charged- Current Neutrino-Nucleon Interactions from a Low-Energy Narrow Band Beam

C. Baltay, H. French, M. Hibbs, R. Hylton, K. Shastri, and A. Vogel
Columbia University, New York, New York 10027

and

P. F. Jacques, M. Kalelkar, P. A. Miller, R. J. Plano, and P. E. Stamer
Rutgers University, New Brunswick, New Jersey 08903

and

E. B. Brucker, E. L. Koller, and S. Taylor
Stevens Institute of Technology, Hoboken, New Jersey 07030

(Received 20 November 1979)

This Letter compares neutral-current and charged-current scaling-variable distributions in neutrino-nucleon interactions induced by a narrow-band beam at Brookhaven National Laboratory; the x distribution of neutral-current events has been reported previously. The first measurement of flux-normalized neutrino cross sections from a narrow-band beam in the energy range $E_\nu = 3-9$ GeV is also presented.

PACS numbers: 13.15.+g, 12.30.Cx

In recent years much has been learned about the structure of nucleons from scaling-variable distributions in lepton-nucleon interactions. In neutrino-nucleon collisions this study has been limited almost exclusively to charged-current interactions,

$$\nu + N \to \mu^- + \text{hadrons}$$

in which there is a muon in the final state. Calculation of the scaling variables requires a knowledge of the neutrino energy, the muon energy and direction, and the hadron energy. In experiments utilizing wide-band beams, one may calculate the neutrino energy as the sum of muon and hadron energies. But in the case of neutral-current interactions,

$$\nu + N \to \nu + \text{hadrons}$$

one cannot calculate the energy of the initial-state neutrino in this fashion because the energy of the final-state lepton is not measurable. In a narrow-band beam, the energy of the incoming neutrino can be inferred from the position of the event and the properties of the beam. Since the direction of the final-state lepton momentum is also unknown, the momentum transfer must be calculated from the properties of the final-state hadrons. This requires an accurate measurement of the direction of the hadron momentum, i.e., a "fine-grain" detector. In this Letter, we report the scaling-variable distributions of neutral-current events induced in a liquid-neon bubble chamber by a narrow-band neutrino beam.[1]

The data consist of pictures taken of the 7-ft cryogenic bubble chamber at Brookhaven National Laboratory, exposed to a two-horn-focused narrow-band neutrino beam designed and built for this experiment. During each accelerator cycle, approximately 7×10^{12} 28-GeV/c protons were incident upon a target to produce secondary pions and kaons; positively charged secondaries of momentum 10 GeV/c (± 10%) were then selected, focused, and allowed to decay into neutrinos and muons in a 60-m tunnel. The decay space was followed by a 30-m iron muon shield, in which counters were placed to monitor the beam intensity, width, and direction throughout the experiment. The bubble chamber was filled with a heavy Ne-H_2 mixture (62 at.% Ne), giving an active fiducial mass of ~ 3 tons. The 157 000 pictures were scanned (40% were scanned twice), and interactions with at least two charged prongs were hand measured. The data were processed through a modified version of TVGP.

Muons produced in the liquid typically leave through the wall of the chamber, whereas hadrons typically stop, interact, or decay in the liquid. We define our charged-current (CC) sample as events with at least one leaving negative track, and a few events with decaying or stopping muon candidates. In the case of more than one leaving negative track (four events) we consider each to be the muon candidate, in turn. We eliminate most events induced by incoming charged particles by requiring that θ_ν, the angle between the visible momentum and the beam direction, be less than 45°; we eliminate cosmic-ray–induced events via a background subtraction using events which have $\theta_\nu > 135°$.

Figure 1 is a scatter plot of the measured visible momentum versus r, the distance from the beam axis, for the CC sample after fiducial cuts. For a narrow-band beam, there is a relationship between the neutrino energy E_ν and r:

$$E_\nu = E_0/\gamma(1-\beta\cos\alpha), \quad \alpha = \tan^{-1}(r/L). \qquad (1)$$

Here E_0 is the energy of the ν in the decay (π or K) $\rightarrow \mu + \nu$ in the parent rest frame, β is the velocity of the parent π or K in the laboratory frame, $\gamma = (1-\beta^2)^{-1/2}$, and L is the distance from the decay point to the detector. A Monte Carlo calculation predicts a spread in E_ν of ±10% at $r = 1$ m. The measured spread in Fig. 1 is larger as a result of measuring errors, undetected hadrons, etc., but the π and K bands are easily distinguishable.

After correcting for hadron punch-through from neutral-current (NC) events (~3 to 5% of NC events) we have 73.4 ν_π events and 13.8 ν_K events in a fiducial mass of 2.1 tons. In order to calculate the flux of neutrinos in the bubble chamber, we have measured the radial distribution and energy distribution of the muons from the π and K decays using ionization counters located at various depths in the muon shield. The counters were calibrated with use of nuclear emulsions.[2] The charged-current cross sections per nucleon are

$$\sigma(\nu_\pi N \rightarrow \mu^- + \text{hadrons})/E_\nu = (0.79 \pm 0.15)\times 10^{-38}\ \text{cm}^2\,\text{GeV}^{-1}, \quad \langle E_\nu\rangle = 3.0\ \text{GeV};$$

$$\sigma(\nu_K N \rightarrow \mu^- + \text{hadrons})/E_\nu = (0.75 \pm 0.23)\times 10^{-38}\ \text{cm}^2\,\text{GeV}^{-1}, \quad \langle E_\nu\rangle = 9.0\ \text{GeV}.$$

These values include the variation of neutrino flux and energy over our detector, and are in agreement with values obtained in other experiments.[3]

Before calculating scaling-variable distributions for the CC events, we make some corrections to the measured hadron energy. For a short interacting track, where a measurement of momentum from curvature is impossible, we estimate the energy from a measurement of the secondary star where possible; otherwise, we add in the energy of the average individual charged hadron, 0.5 GeV. For a failing electron track in a detected γ, we add in the energy of the average nonfailing electron in a γ, 0.3 GeV; we also add 0.6 GeV to E_H if the number of detected γ's is odd. Finally, we correct for the worst cases of undetected neutral hadrons; if the visible momentum of a ν_π (ν_K) event is more than 0.75 (2.25) GeV/c below the value predicted by Eq. (1), the hadron energy is taken to be the predicted neutrino energy minus the muon energy. The average hadron-energy correction is 7%. Expanding the fiducial volume somewhat we have 120 CC events.

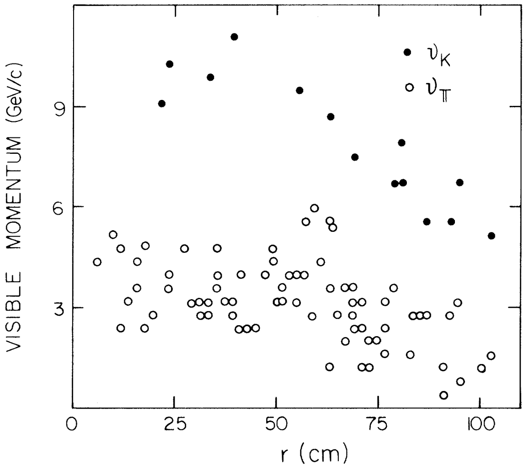

FIG. 1. Scatter plot of measured visible momentum vs distance from beam axis for charged-current events.

Figures 2(a) and 2(b) show how these events are distributed in x and y, where

$$x = q^2/2M(E_\nu - E_\mu),$$

$$y = E_H/E_\nu.$$

Here E_H(q^2) is the energy (square of the four-momentum) transferred to the hadrons and E_ν is the visible energy, $E_\mu + E_H$. The y distribution is essentially flat.

The quantity $\langle q^2/E_\nu\rangle$ is particularly free from systematic errors in charged-current interactions, since (except for binning in E_ν) it depends solely upon the muon measurement: $q^2/E_\nu = 2E_\mu(1-\cos\theta_\mu)$. It is a sensitive test of scaling since $\langle q^2/E_\nu\rangle = 2M\langle xy\rangle$; if the x and y distributions are independent of E_ν, then $\langle q^2/E_\nu\rangle$ should be also. Using the hadron measurements solely to distinguish between ν_π and ν_K events (see Fig. 1) we find, for $\nu_\pi \rightarrow \mu^-$,

$$\langle q^2/E_\nu\rangle = 0.30 \pm 0.02\ \text{GeV}/c^2, \quad \langle E_\nu\rangle = 3.0\ \text{GeV};$$

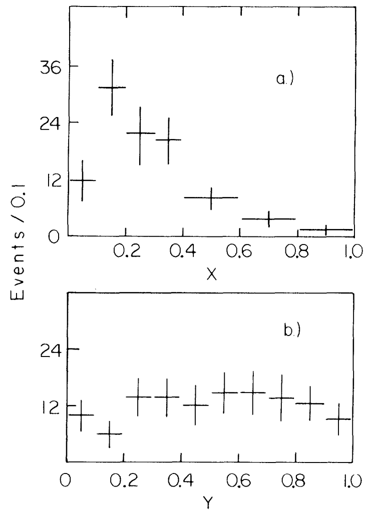

FIG. 2. Scaling-variable distributions for charged-current events: (a) x distribution, (b) y distribution.

for $\nu_K \to \mu^-$,

$$\langle q^2/E_\nu \rangle = 0.21 \pm 0.05 \text{ GeV}/c^2, \quad \langle E_\nu \rangle = 9.0 \text{ GeV}.$$

The gentle decrease of $\langle q^2/E_\nu \rangle$ agrees with the breaking of scale invariance observed over a wide range of neutrino energies.[4]

To isolate neutral-current events we retain events without leaving negative tracks only in the region where the signal is significant above background, events which have $\theta_H < 60°$ and which dip no more than 30° below horizontal. θ_H is the angle between the hadron momentum vector and the beam direction. We eliminate effects of residual neutral-cosmic-ray-induced contamination via a background subtraction using events which have $\theta_H > 120°$. To eliminate beam-associated background (neutron-induced events, etc.) we make two cuts. We require that the quantity $\lambda = (E_\nu - E_H)^2 - (\vec{P}_\nu - \vec{P}_H)^2$ lie in the range -3.5 GeV$^2 < \lambda < 1.0$ GeV^2. Here E_ν is the incoming neutrino energy as calculated from Eq. (1); we assume that the neutrino is from π decay unless $E_\nu(\pi) < E_H$. λ is the on-mass-shell constraint of the final-state neutrino and would be zero if our detector had 100% efficiency and precision and the beam were monochromatic. 80% of the charged-current events have λ (of the final-state muon) within this range. We also require that the measured hadron momentum be above 650 MeV/c. After all cuts we have 23 neutral-current events. Imposing these cuts on the CC sample as well, we find that the ratio of neutral-current to charged-current events is

$$R_\nu = 0.32 \pm 0.11.$$

Since this value is in agreement with other experiments,[5,6] and the NC events are uniformly distributed in the fiducial volume, and the NC and CC λ distributions have similar shapes within the range used, we conclude that the remaining background in the neutral-current sample is small (10 ± 10%).

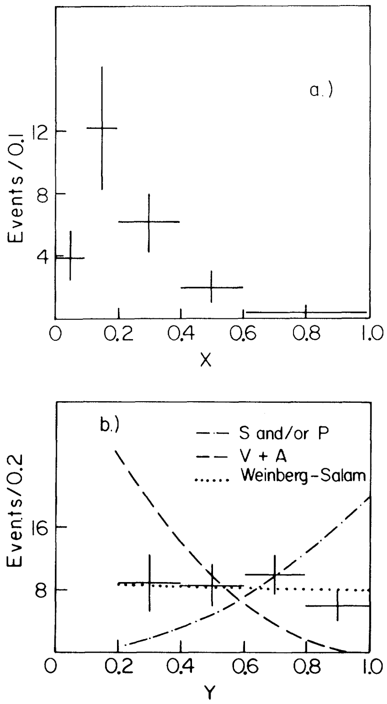

FIG. 3. Scaling-variable distributions for neutral-current events: (a) x distribution, (b) y distribution (the flat $V-A$ prediction is virtually identical to the Weinberg-Salam curve).

For NC events we must calculate distributions in the scaling variables x and y using the initial-state neutrino energy from Eq. (1) and obtaining the final-state neutrino momentum from momentum conservation, $\vec{P}_{\nu'} = \vec{P}_\nu - \vec{P}_H$. In principle these distributions may be distorted from the "true" NC distributions by two effects: (1) the loss of events in some regions of phase space due to the cuts made; and (2) the loss of precision in x and y caused by the nonzero width of the narrow-band beam. To investigate these effects, we have calculated x and y distributions for the charged-current events after imposing the NC cuts, ignoring the muon measurement, and taking the incoming neutrino energy from Eq. (1);

i.e., treating the CC events in the same way we treat NC events. Comparing these distributions with those of Fig. 2 allows us to estimate the distortions of the neutral-current selection and calculation procedure, and to correct for them in a model-independent fashion. The overall normalization correction is 38%; however, for events which have $y > 0.2$, the corrections to the shapes of the distributions are small (1.2 standard deviations per bin in x and y, on the average). Our average resolution in x and y is 0.2. After correcting the neutral-current sample for both normalization and shape, we obtain the scaling-variable distributions of Figs. 3(a) and 3(b). No correction is possible for $y < 0.2$ since the cut on P_H eliminates nearly all events in this region.

Comparing Figs. 2(a) and 3(a), we conclude that the NC and CC x distributions are very similar, in agreement with the parton-model prediction for valence quarks in the Weinberg-Salam theory of weak interactions.

The shape of the neutral-current y distribution has been used by counter experiments[6] in narrow-band beams at higher energies to test the space-time structure of the NC interaction.[7] Normalizing the predicted algebraic form to our total number of events, we find that a pure scalar and/or pseudoscalar interaction ($dN/dy \propto y^2$) is inconsistent with our data (χ^2 per degree of freedom $=39/3$), as is pure $V + A$ [$dN/dy \propto (1-y)^2$, χ^2 per degree of freedom $= 25/3$]. Pure $V - A$ ($dN/dy = \text{const}$) and the Weinberg-Salam model with $\sin^2\theta = 0.25$ [$dN/dy \propto 1 + \frac{5}{41}(1-y)^2$] both agree with our data; we do not have sufficient statistics to distinguish between them (χ^2 per degree of freedom $=2.1/3$ and $1.9/3$, respectively). Our results are compatible with the higher-energy experiments, which prefer Weinberg-Salam over $V - A$; i.e., our data do not contradict the scaling hypothesis that the space-time structure of neutral currents is independent of the incoming neutrino energy.

Another quantity of interest is $\langle q^2/E_\nu\rangle_{\rm NC}/\langle q^2/E_\nu\rangle_{\rm CC} = \langle xy\rangle_{\rm NC}/\langle xy\rangle_{\rm CC}$. In the Weinberg-Salam model, this quantity is restricted[8] to the range 0.61–1.0 by the requirement $0 < \sin^2\theta < 1$, with values near unity indicated by currently accepted values of the Weinberg angle (~ 0.98 for $\sin^2\theta = 0.25$). Compensating for our lack of events below $y = 0.2$ by using only events in the range $0.2 < y < 0.8$, we obtain

$$\langle xy\rangle_{\rm NC}/\langle xy\rangle_{\rm CC} = 0.94 \pm 0.21,$$

in agreement with the Weinberg-Salam model.

We wish to thank L. Repeta and G. Smith of Brookhaven National Laboratory for their work in design and construction of the beam, the operating crews of Brookhaven National Laboratory, and our scanning and measuring personnel.

---

[1] For a summary of work in progress to measure the NC x distribution at higher energies, see the article by the CHARM collaboration, in Proceedings of the Fermi Lepton-Photon Symposium, August, 1979 (to be published).

[2] A. Vogel, Ph.D. thesis, Columbia University (to be published).

[3] For a recent compilation see S. Ciampolillo *et al.*, Phys. Lett. 84B, 281 (1979).

[4] For a recent compilation see D. S. Baranov *et al.*, Phys. Lett. 81B, 258 (1979).

[5] J. Blietschau *et al.*, Nucl. Phys. B118, 218 (1977).

[6] M. Holder *et al.*, Phys. Lett. 72B, 254 (1977); F. S. Merritt *et al.*, Phys. Rev. D 17, 2199 (1978).

[7] B. Kayser *et al.*, Phys. Lett. 52B, 385 (1974).

[8] L. M. Sehgal, Nucl. Phys. B65, 141 (1973).