less than 10% for different parametrizations.

[4]F. Weisser *et al.*, to be published; F. Weisser, Ph.D. thesis, Carnegie-Mellon University, 1972 (unpublished).

[5]If we allow one more term in the expansion, we find $A_2 = 0.83 \pm 0.24$, $A_4 = 0.48 \pm 0.31$, $A_6 = 0.47 \pm 0.75$, with A_0 set equal to 1.

[6]The width of the observed enhancement is much larger than that of the D meson; hence we attribute the enhancement entirely to the four-pion decay of the f^0 meson.

[7]Because of different scanning and measurement corrections for the two samples, a normalization is necessary.

[8]We have verified that the predictions of this model are insensitive to the assumed width of the ρ meson and the $f_{\rho\pi\pi}$ form factor. We wish to thank Professor Ascoli for his comments on this point.

[9]These coefficients have been obtained from a Monte Carlo sample of 10 000 $f^0 \to \pi^+\pi^+\pi^-\pi^-$ events. These events were generated according to the $\rho\rho$ model of Ascoli *et al.* For the f^0 mass distribution in the Monte Carlo model, the experimentally observed $f^0 \to \pi^+\pi^+\pi^-\pi^-$ mass distribution was assumed.

[10]L. Banyai and V. Rittenberg, Nucl. Phys. B15, 199 (1970). We thank Professor Rittenberg for helpful comments regarding this model.

[11]A comparison of predictions of the two models with the experimental distributions yields the following results. For the model of Banyai and Rittenberg the χ^2 per degree of freedom is 6.1, 2.6, and 5.2 for the distributions in Figs. 2(b), 2(c), and 2(d), respectively. For the $\rho\rho$ model we obtain a χ^2 per degree of freedom equal to 1.9, 1.2, and 2.2 for the same distributions.

Exploratory Study of High-Energy Neutrino Interactions*

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We report the results of an initial investigation of high-energy neutrino interactions using a dichromatic neutrino beam. Two bands of neutrinos, from pion decay ($\langle E_\nu \rangle \approx 50$ GeV) and kaon decay ($\langle E_\nu \rangle \approx 145$ GeV), were incident on a counter–spark-chamber detector. We discuss analysis of events of the type $\nu_\mu + N \to \mu^- +$ hadrons. Qualitative comparisons are made with lower-energy neutrino results and the deep-inelastic e-N scaling structure functions.

An exploratory study of high-energy neutrino interactions was carried out in a dichromatic beam at the National Accelerator Laboratory in January 1973.[1] The purposes of this brief preliminary run were to study our apparatus, investigate the qualitative features of high-energy neutrino interactions, and to look for possible anomalous effects. An improved lower bound on the W-boson mass and a preliminary search for a heavy muon have been reported from this run.[2]

We report here on the qualitative results obtained from neutrino interactions of the type

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

In order to study all the relevant features of this reaction, we have constructed an experiment which measures the hadron energy E_h, the muon energy E', and muon lab angle θ'. This allows determination of the invariant kinematic variables: four-momentum transfer Q^2 and energy transfer ν to the hadron system.

It is beyond the purview of this paper to describe in detail the apparatus and beam. Briefly, a momentum and sign-selected secondary hadron beam is created from the interactions of primary protons from the accelerator, and is directed down a 345-m decay pipe in which kaon and pion decays yield neutrinos and muons. The muons and nondecaying hadrons are removed by 530 m of dirt and steel shielding. The resulting neutrino beam consists of low- and high-energy bands of muon neutrinos from the decays $\pi^+ \to \mu^+ + \nu_\mu$ and $K^+ \to \mu^+ + \nu_\mu$, respectively.

To investigate neutrino interactions, we have constructed a 160-ton steel target interspersed with liquid scintillation counters and wire spark chambers. This target detector is followed by a toroidal iron core magnet and four additional spark chambers to measure the angle of deflection of the secondary muon and thus its energy E'. The hadron energy E_h is determined by calorimetry in 1.5×1.5-m liquid scintillation counters located after each 10 cm of steel. Muons are identified by penetration; the muon lab angle θ' is determined by the wire spark chambers located in the target.

The data reported in this paper were obtained in a run of 2.7×10^{16} protons on target. The hadron beam was tuned for 160-GeV/c positive secondaries with a ±11% momentum bite. As a result of this run, 167 neutrino events have been identified. Cosmic-ray and accelerator associated backgrounds are negligible. To facilitate the analysis, geometric fiducial cuts have been imposed on the data which reduced our sample to 145 events. We have further eliminated events which have either muon momentum or hadron energy that could not be determined for instrumental reasons; this reduced the sample to 112 reconstructible events. For 97 of the reconstructed events, all the secondary hadron energy was directly observed; in the other 15, one of the many pulse-height analyzers in the calorimeter saturated, allowing only a lower limit to be set on the hadron energy. Any biases introduced by these sample reductions are unimportant at the statistical level of results presented in this paper.

The measured energy spectrum $E_{\text{tot}}=E'+E_h$ for neutrino interactions in our apparatus is shown in Fig. 1. The expected ranges in energy for pion and kaon neutrinos are determined by the secondary beam momentum spread and the angular acceptance of the target. These ranges are also shown in Fig. 1. Two peaks of about the right width and mean energies are seen. Also it should be noted that only 1 out of 112 events had a μ^+ rather than a μ^- in the final state. We believe this is because of antineutrino contamination[2] ($\bar{\nu}_\mu+N\to\mu^++\text{hadrons}$). Improvements have recently been made to the beam which shoud significantly reduce this background in the future.

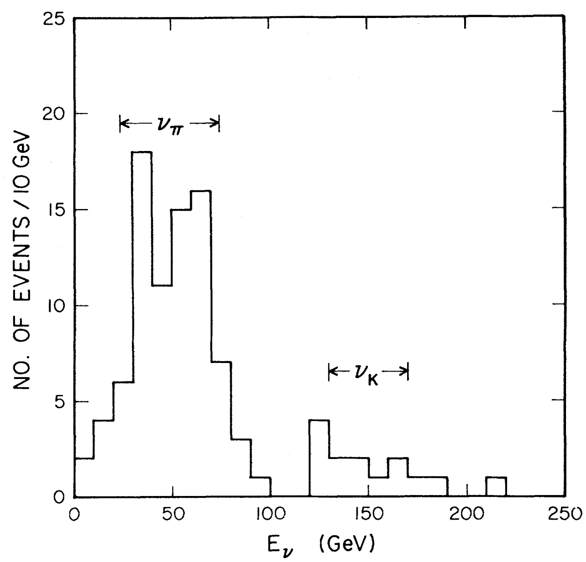

FIG. 1. The energy distribution $E_\nu=E'+E_h$ of the observed events. Also indicated are the expected widths due to the momentum spread of the hadron beam (±11%) and the angular acceptance of the apparatus. The additional spread of the actual events is due to the resolution E' and E_h in our apparatus.

Of the 112 events, 94 events have been identified as pion-decay neutrinos, $\langle E_\nu\rangle\simeq 50$ GeV, and 18 events have been identified as kaon-decay neutrinos, $\langle E_\nu\rangle\simeq 145$ GeV. In order to study the qualitative features of the interaction, we have first concentrated on the more statistically significant pion neutrinos.

Our approach has been to calculate the "expected" behavior by using the results from low-energy neutrino scattering and the form of the structure functions from deep-inelastic electron scattering. We have then compared our data with this predicted behavior.

The differential cross section[3] under the scaling assumption for the structure functions can be written as

$$\frac{d^2\sigma^{\nu N}}{dx\,dy}=\frac{G^2ME_\nu}{\pi}\{(1-y)F_2(x)+\tfrac{1}{2}y^2[2xF_1(x)]-y(1-\tfrac{1}{2}y)xF_3(x)\},\quad x\equiv Q^2/2M\nu,\quad y\equiv\nu/E_\nu. \tag{2}$$

Terms of order M/E_ν, where M is the nucleon mass, have been ignored. To simplify the analysis, we have assumed that (i) $2xF_1(x)=F_2(x)$. This is the Callan-Gross relation[4] and is valid for scattering off spin-$\frac{1}{2}$ constituents in parton models. (ii) $xF_3(x)=-F_2(x)$. This is valid for scattering from spin-$\frac{1}{2}$ partons (no antipartons) with pure $V-A$ coupling.

These assumptions appear at least qualitatively valid from CERN data[3,5] and Stanford Linear Accelerator Center data.[6,7] In particular, the longitudinal cross section is observed to be small in e-p scattering.[7] Also, the distribution in y for

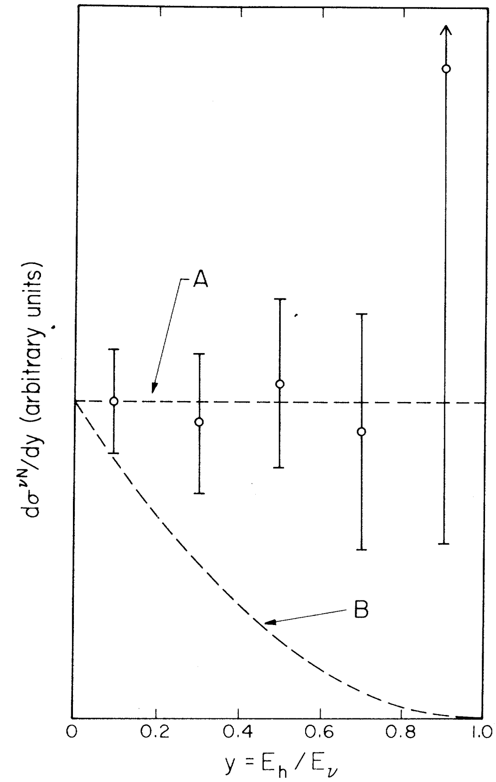

FIG. 2. The distribution $d\sigma^{\nu N}/dy$ (arbitrary units) versus y for the pion-decay neutrinos, where $y = E_h/E_\nu$. Curve A shows the behavior expected for neutrinos scattering off spin-$\frac{1}{2}$ point particles (quarks), while curve B shows the expected behavior for antineutrinos. It should be noted that neutrinos scattering off spin-$\frac{1}{2}$ antiparticles (antiquarks) give curve B.

low-energy $\bar{\nu}$ scattering and the ratio of ν to $\bar{\nu}$ cross sections observed at low energy are qualitatively consistent with (i) and (ii). If we assume that the small measured deviation ($\sigma_{\bar{\nu}}/\sigma_\nu = 0.38 \pm 0.02$ instead of 0.33)[3] is due to an antiquark contribution in (ii), the results discussed here are unaffected.

Under these quark-model assumptions, the cross sections can be written in terms of only one structure function

$$d^2\sigma^{\nu N}/dx\,dy \approx (G^2 M E_\nu/\pi) F_2(x), \qquad (3)$$

$$d^2\sigma^{\bar{\nu} N}/dx\,dy \approx (G^2 M E_\nu/\pi)(1-y)^2 F_2(x). \qquad (4)$$

This means that for neutrino scattering the y distribution should be nearly flat, while antineutrino scattering has a strong y dependence. A small antiquark contribution makes only a slight modification to this behavior. The x distribution is determined by the structure function $F_2(x)$, which can be directly related in a quark parton model

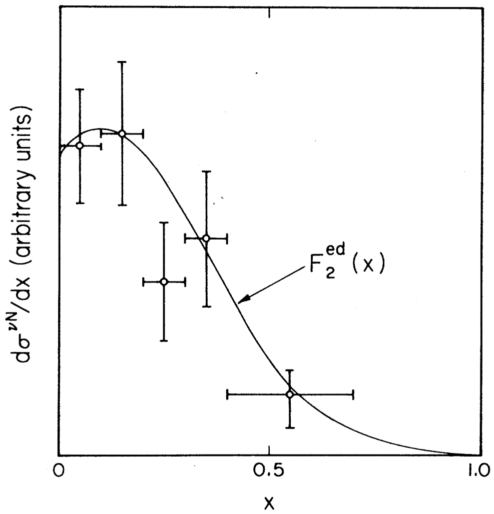

FIG. 3. The distribution $d\sigma^{\nu N}/dx$ (arbitrary units) versus $x = Q^2/2m\nu$ (the scaling variable). For comparison, the fit for $F_2^{ed}(x)$ (Ref. 6) is shown.

to $F_2^{ed}(x)$, the structure function for electron-deuteron inelastic scattering.[6] This analysis assumes that corrections for the isoscalar part of F_2^{ed}, breakdowns of chiral symmetry, etc., are small.

Figure 2 shows the y distribution of the pion neutrino events corrected by the efficiency calculated from a Monte Carlo program. The data are qualitatively consistent with the expected nearly flat y distribution. For comparison, the expected y distribution for antineutrino scattering is shown. Figure 3 shows the x distribution for the data obtained in a similar manner. Within the limited statistical accuracy of the data, agreement with $F_2^{ed}(x)$ is quite good.

We can say, therefore, that at $\langle E_\nu \rangle \approx 50$ GeV these distributions are qualitatively consistent with a simple spin-$\frac{1}{2}$ constituent model. Considering that the input to the model came from electron scattering and low-energy $\sigma_{\bar{\nu}}/\sigma_\nu$ ratio, the agreement at the present statistical level is already impressive.

Given the qualitative agreement of the x and y distributions, we have pursued our analysis one step further by investigating the dependence on neutrino energy. An important test is to see if the behavior of Eq. (3) becomes modified at high energies (e.g., by effects of a W propagator, by a breakdown of scaling of the structure functions, etc.). With the assumption of scaling behavior, it can be shown that $\langle Q^2 \rangle$ should grow linearly with E_ν. Only the Q^2 distributions at different

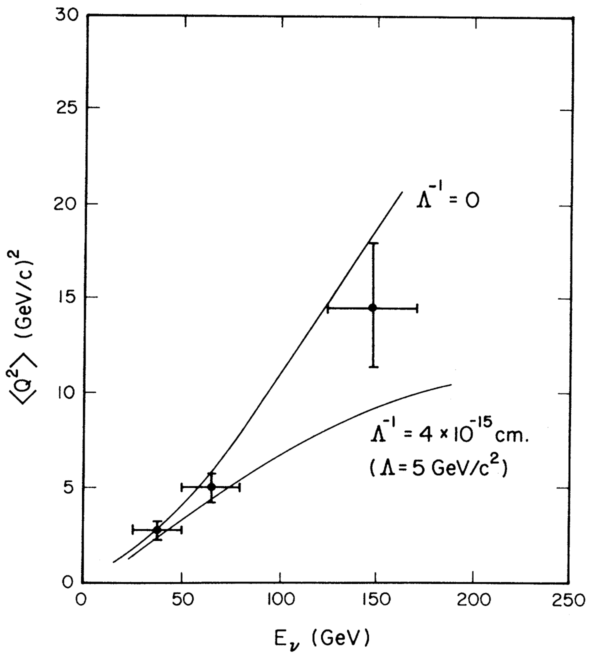

FIG. 4. $\langle Q^2 \rangle$ versus E_ν is plotted for events detected in the apparatus. For comparison, the expected behavior (including effects of detection efficiency) is shown for the simple case of Eq. (5). The behavior assumed for $F_2(x)$ is the same as $F_2^{ed}(x)$. A curve is shown both for $\Lambda^{-1} = 0$ and $\Lambda^{-1} = 4 \times 10^{-15}$ cm.

values of E_ν are required for this test.[5]

Because our apparatus does not cover the complete kinematic range, we do not expect a precisely linear behavior for the accepted events. Figure 4 shows the expected $\langle Q^2 \rangle$ in our apparatus as a function of E_ν assuming expression (3) and $F_2^{ed}(x)$ for the x behavior of $F_2(x)$. For comparison, the pion neutrino events are shown in two bins, one with $\langle E_\nu \rangle = 38$ GeV and one with $\langle E_\nu \rangle = 65$ GeV; for the kaon neutrinos $\langle E_\nu \rangle = 148$ GeV. The data are consistent with the expected Q^2 behavior.

In order to test the sensitivity to scaling, we have assumed a particular form for a potential breakdown:

$$\frac{d^2\sigma^{\nu N}}{dx\,dy} = \frac{G^2 M E_\nu}{\pi} \frac{F_2(x)}{(1 + Q^2/\Lambda^2)^2}. \qquad (5)$$

The additional factor could be due to a W-boson propagator or could be one possible form for a breakdown of hadronic scaling (i.e., nonpointlike behavior). To indicate the present level of sensitivity, a curve for $\Lambda = 5$ GeV/c^2 is shown in Fig. 4.

In summary, our data at $E_\nu \sim 50$ GeV are qualitatively consistent with scattering predominantly off spin-$\frac{1}{2}$ pointlike particles. Also, the dependence of $\langle Q^2 \rangle$ versus E_ν agrees with pointlike scaling behavior, at least down to distances like $1/\Lambda \sim 4 \times 10^{-15}$ cm.

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