This experiment was carried out in the FNAL dichromatic neutrino beam. Neutrinos interacting in a 170 ton iron target through the process
\[ \nu + N \rightarrow \mu^- + \text{hadrons} \]
are selected when the muon traverses a trigger counter located downstream of the magnet. The muon and hadron energies \( E'_\mu \) and \( E_h \) are measured to the following accuracy:
\[ E'_\mu : \text{statistically 21\%, systematically 5\%} \]
\[ E_h : \text{statistically 14-30\% systematically 10\%} \]
The distribution in total observed energy \( E_{\text{obs}} = E'_\mu + E_h \) is shown in Figure 1. The characteristic two peak structure expected in a narrow band beam is clearly seen. The mean neutrino energies of the peaks are \( <E'\nu> = 40 \text{ GeV} \) and \( <E_h> = 140 \text{ GeV} \).

1 DISTRIBUTION IN THE SCALING VARIABLE \( x = Q^2/2m_h \)
Precise measurement of \( x \)-distributions require extremely good resolutions. Resolution effects change the shape of observed \( x \)-distributions as shown in Figure 2a. The curve labelled \( F_2(x) \) is the structure function measured by SLAC-MIT with electrons on deuterium. When we fold in the experimental resolutions for this experiment, we find the expected experimental curve labelled \( \langle F_2(x) \rangle \) smeared.

Fig. 1 Visible energy distribution showing two-peak structure characteristic of a narrow band beam.

Fig. 2 Comparison of our data with the \( x \) distribution expected from electron-deuterium data after folding in our experimental resolution and acceptance.
If we further fold in the acceptance of the apparatus, we see the lower curve. Therefore, it should be emphasized that an $F_2(x)$ structure function of the same form as that obtained at SLAC will result in an experimental distribution that is sharply peaked near $x = 0$, and with a somewhat different falloff, coming from effects of resolution and acceptance. Figure 2b shows the observed $x$-distribution for the 1027 events inside our fiducial volume where both the muon and the hadron energies are measured. The solid curve is the expected distribution, assuming the SLAC $F_2^{ed}(x)$ structure function with resolutions and efficiencies folded in. There are no statistically significant differences observable between the $x$-distribution for pion neutrinos and kaon neutrinos.

2 TEST OF SCALING IN THE $Q^2$ DISTRIBUTION

The distribution in $Q^2$ corrected for efficiency, for all events is shown in the figure 3a. The expected distribution shown as the smooth curve, assumes the flat $y$-distribution as well as $F_2^{ed}(x)$ from SLAC. This curve is labelled $\Lambda = \infty$ in the figure. In order to test the sensitivity of the data to a possible breakdown of scaling or a propagator effect we have also included a multiplicative term $(1 + Q^2/\Lambda^2)^{-2}$, which modifies the expected behaviour giving a steeper falloff. For $\Lambda = 10$ GeV, for example, the calculated curve normalized to the data falls below the data at all points below the first. Figure 3b shows the confidence level for a fit to this propagator term. Above $\Lambda = 15$ GeV/c$^2$ we have no sensitivity; the fit is equally likely at $\Lambda = \infty$. Below 15 GeV/c$^2$, the likelihood falls rapidly. We place a 90% confidence on a propagator mass for the term we have included: $\Lambda > 10.3$ GeV/c$^2$.

3 DISTRIBUTIONS IN THE INELASTICITY VARIABLE $y = E_h/E_\nu$.

The $y$-distributions are more affected by the acceptance function than by resolution. The smooth curve shown in figure 4a is the expected $y$-distribution observed in our apparatus for $\nu$ interactions; effectively, it corresponds to the efficiency of the apparatus in the variable $y$. The data are shown on the same figure with the appropriate statistical error. Figure 4b shows the same distribution on a log scale. The systematically high points for $y > 0.6$ occur in a region where the efficiency has fallen below 10%. Below this value where the efficiency is high and well understood, there are no systematic departures from the expected flat distribution for neutrinos. We have chosen to
analyze our data for $y < 0.6$ only.

Figure 5a shows all the neutrino events with $y < 0.6$ corrected for efficiency and plotted vs. $y$. The data are consistent with the expected flat distribution. To obtain a numerical estimate of this consistency, we have fit to a function of the form

$$
\frac{dN}{dy} = C \left(1 + a(1-y)^2\right)
$$

where $C$ is constrained by the overall normalization, and $a$ is a free parameter (it could be thought of as representing an average antiquark component in the nucleon). Figure 5b shows the result:

$$
a = 0.05 \pm 0.25
$$

consistent with zero, and consistent with the 5% average anti-quark component found in the low energy CERN data.

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**Fig. 4** Comparison of our data with a flat $y$ distribution modified by our acceptance on (a) linear and (b) logarithmic scales.

**Fig. 5** Distribution in $y$ for $y < 0.6$ fitted to determine the average antiquark component in the nucleon.

**Fig. 6** Measured neutrino and antineutrino cross sections. The inner error bars represent the statistical errors and the outer ones the total errors.
The cross-section has been measured in a separate run using the FNAL narrow band beam. This is the first measurement of $\sigma_\nu$ and $\sigma_\nu^-$ at NAL energies in which the neutrino flux is measured directly in the same experiment. A more complete description of the experimental method used will be found in the paper submitted to the conference: (Paper 582; CALT-68-452.) Figure 6 shows the cross-sections measured in this experiment with statistical errors extending to the inner horizontal bars. The estimated systematic errors have been added in quadrature; the total errors are drawn to the outer horizontal bars. The best fits for $\sigma_\nu$ and $\sigma_\nu^-$ are

$$\sigma_\nu = (0.83 \pm 0.11) \times 10^{-38} \text{ cm}^2/\text{GeV} \quad (2)$$

$$\sigma_\nu^- = (0.28 \pm .055) \times 10^{-38} \text{ cm}^2/\text{GeV} \quad (3)$$

The data points are quite consistent with this assumed linear relationship intersecting the origin. Figure 7a shows the ratio of anti-neutrino to neutrino cross-sections at the two neutrino energies in this experiment. The ratio of slopes (equations (2) and (3)) is shown as the solid horizontal line. The sum of the slopes is shown in figure 7b, with the best fit line shown as well. For scattering dominantly from particle constituents of spin 1/2 (quarks) through V-A reaction, the ratio of $\sigma_\nu/\sigma_\nu^-$ is equal to 1/3. The deviation from this value is a measure of the anti-quark component in the nucleon and/or breakdown of the Callan-Gross relation. Figure 8 shows the relative fraction of anti-quark ($Q/Q$) and spin 0 ($K/Q$) component. The Callan-Gross relation would predict $K = 0$.

The slope ratio persists at high energy with a value close to 1/3. However, the higher energy experiments are still not able to determine the presence of anti-quarks at the 5% level.

In parton models, the sum of the slopes ($\sigma_\nu + \sigma_\nu^-$) in neutrino and anti-neutrino scattering from nucleons

$$\sigma_\nu = \frac{G^2}{2\pi} \left[ \frac{Q}{3} + \frac{1}{3} Q + \frac{1}{2} K \right]$$

$$\sigma_\nu^- = \frac{G^2}{2\pi} \left[ \frac{Q}{3} + \frac{1}{3} Q + \frac{1}{2} K \right]$$

Fig. 8 One standard deviation limits imposed on the antiquark and spin - 0 components in the nucleon in this and the CERN experiments.
is related to the magnitude of the electro-magnetic scattering from nucleons through the mean-square charge of the constituents. This relationship may be expressed as follows

\[
\langle q^2 \rangle = \frac{\int F_N^N(x) \, dx}{\frac{3}{4} \frac{a}{M} (a_y + a_v)}
\]

(6)

where \( \langle q^2 \rangle \) is the mean square charge of the constituents in units of the electron charge, the numerator is the integral over the structure function, \( F_N^N(x) \), measured in electron-deuteron deep inelastic scattering, with the contribution from strange quarks subtracted. We have taken here

\[
\int F_N^N(x) \, dx = 0.15 \pm 0.02
\]

For scattering from constituents that have fractional charge (e.g., quarks), or fractional effective charge (e.g., Han-Nambu quarks below colour threshold), one expects relatively small values for \( \langle q^2 \rangle \). For example, the simplest quark model would give \( \langle q^2 \rangle = \frac{5}{18} = 0.28 \). Integral charges for the constituents, on the other hand, require \( \langle q^2 \rangle \geq 0.5 \).

We see from figure 9 that the relatively small value for \( \langle q^2 \rangle \) continues at 38 and 105 GeV. Averaging the data from this experiment, we obtain for \( E_\nu > 30 \text{ GeV} \)

\[
\langle q^2 \rangle = 0.27 \pm 0.05
\]

in agreement with that expected for scattering from quarks.

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Fig. 9 Mean square charge of the nucleon constituents derived from \( F_N^N \) and the sum of neutrino and anti-neutrino cross sections.