gular divergence, and the invariant-mass distribution of the electron pairs do not explain the observed experimental results. The discrepancies are rather large, e.g.,

$$\sigma_{\text{pair}}(\text{theory}) \gg 5\sigma_{\text{pair}}(\text{experiment})$$

in particular, for small E_0 and Q regions. Nuclear emulsion has a large detection efficiency for even extremely low-energy particles and here we have been able to detect electrons with kinetic energy <1 MeV. We feel that the present systematic experimental observations will be useful to the theorists who wish to look into these discrepancies very seriously.

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Observation of Muonless Neutrino-Induced Inelastic Interactions

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We report the observation of inelastic interactions induced by high-energy neutrinos and antineutrinos in which no muon is observed in the final state. A possible, but by no means unique, interpretation of this effect is the existence of a neutral weak current.

We report here additional results of our study[1] of high-energy neutrino interactions produced by the broad-band unfocused neutrino beam of the National Accelerator Laboratory. In this note we concentrate on reactions which are distinguished from the "ordinary" processes, $\nu_\mu(\bar{\nu}_\mu)$ + nucleon $\to \mu^-(\mu^+)$ + hadrons, by the absence of a muon in the final state. Data obtained with proton energies $E_p = 300$ and 400 GeV are presented here.

The experimental setup is shown in Fig. 1(a). The light from each of the sixteen segments of the target-detector was collected to generate a pulse proportional to the energy deposited in each segment.[2] The sixteen signals were combined to generate an event trigger whenever the total energy[3] exceeded a specific threshold (6 GeV at $E_p = 300$ GeV, 12 GeV at $E_p = 400$ GeV). The detector was gated on during two equal periods, one coincident with the machine burst, the other delayed to detect cosmic-ray events exclusively. At $E_p = 300$ GeV (400 GeV) the effective beam-spill duration was 100 μsec (15 μsec). For each

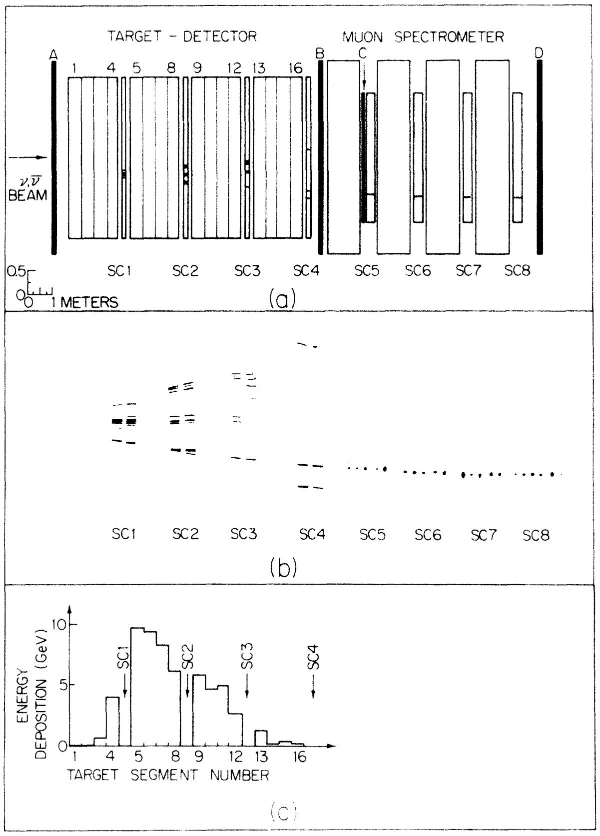

FIG. 1. (a) Plan view of experimental apparatus. The target-detector consists of liquid-scintillator segments (1–16) with wide-gap spark chambers ($SC1$–$SC4$) interspersed, each with two gaps. The muon spectrometer consists of four magnetized iron toroids whose axes coincide with the beam line. After each toroid are narrow-gap spark chambers ($SC5$–$SC8$) each with six gaps. Auxiliary scintillation counters are labeled A, B, C, and D. A typical inelastic neutrino event with an associated muon is sketched into the spark chambers. Its enlarged photograph appears in (b) and the energy deposition in each segment is shown in (c).

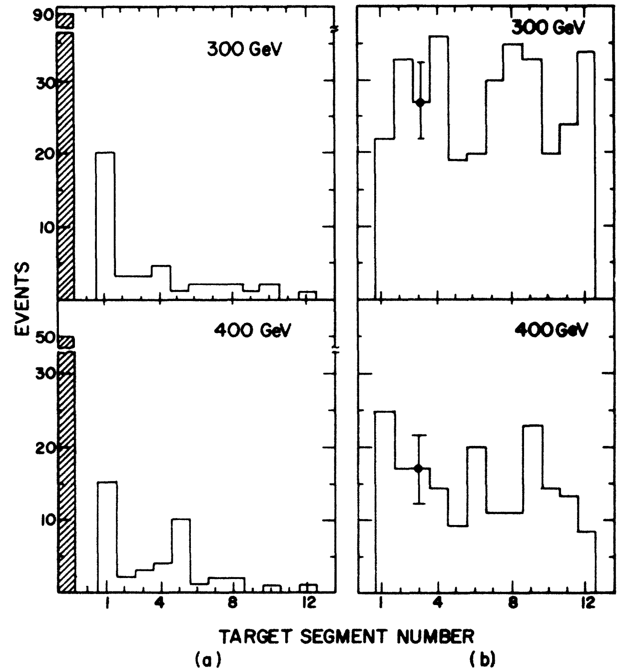

FIG. 2. (a) Distributions of event vertices along the neutrino beam path for events in which counter A fired. The crosshatched bins contain all events with a vertex upstream of the detector. (b) Events that did not fire A.

event we triggered all spark chambers and recorded on magnetic tape the energy deposited in each target segment, and the pattern and relative timing of the auxiliary scintillation counters A, B, C, and D [Fig. 1(a)].

The subdivision of the target-detector and the good multispark efficiency of the wide-gap chambers, coupled with the high multiplicity of the interactions, led to unambiguous identification of the hadron cascade. The position of the vertex of the primary interaction was determined by the distribution of the energy depositions in the target-detector and by extrapolation of the spark-chamber tracks with a precision of ± 5, ± 15, and ± 25 cm in the vertical, horizontal, and longitudinal coordinates, respectively.

Results are based on 1116 triggers at $E_p = 300$ GeV and 368 triggers at 400 GeV. None of the 92 triggers within the cosmic-ray gate had a clear vertex within or just outside the target volume. The longitudinal distribution of vertices for events within the beam gate and with a good vertex is shown in Fig. 2, divided into two groups depending on whether or not counter A fired. As Fig. 2(a) shows, the majority of events with a pulse in A have vertices either upstream of or in the first segment of the target-detector. The vertices of those events occurring inside the target are attenuated in 1.5 target segments, about 1 strong-interaction absorption length. The residual flat contribution is consistent with accidental counts in A. Vertices for events in which A did not fire [Fig. 2(b)] have a distribution uniform over 7 absorption lengths, indicating that interactions of neutrons entering the front of the apparatus are insignificant.

The vertex distribution in the plane perpendicular to the beam is shown in Fig. 3 for events with no count in A. Hadrons entering from the

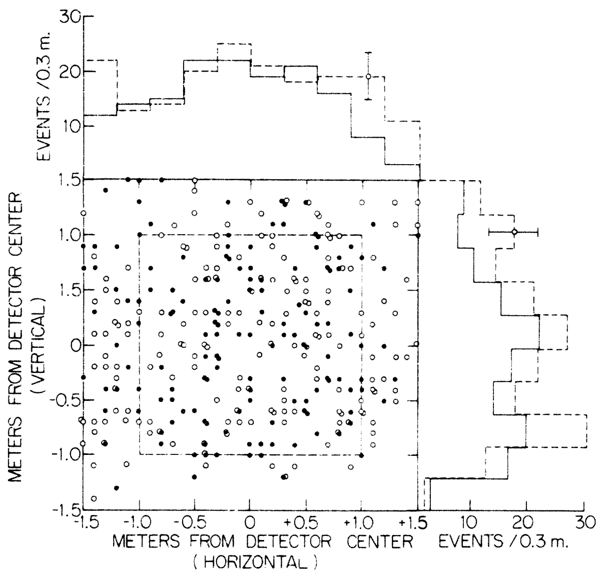

FIG. 3. Distribution of event vertices in the plane perpendicular to the beam (data for $E_p = 300$ GeV only). Filled circles depict events with a muon and open circles events without a muon. Projections onto the horizontal and vertical axes represent muon events by solid lines and muonless events by dashed lines. Vertices within the dashed square satisfy the final fiducial-volume requirement.

sides would have a transverse attenuation length equal to 1 absorption length times their mean angle with respect to the beam direction. The angles of the observed hadron showers have been measured and have a distribution centered on 0 mrad projected angle with a rms deviation of 25 mrad. The absence of any substantial enhancement near the edges of the target indicates that there is no appreciable background of hadrons penetrating from the sides.

To ensure good containment of the hadronic cascade, moderately high muon detection efficiency, and rejection of possible hadrons incident from the sides, fiducial-volume cuts are imposed: The vertex must occur within the first twelve target segments and be at least 0.5 m away from the edges. After these cuts the total number of events is 236 at 300 GeV and 94 at 400 GeV.

The presence of an associated muon in the spectrometer was identified independently by a count in C or by observation of a track in $SC5$ [Fig. 1(a)]. The only correction is for wide-angle muons that miss the muon identifier. The geometrical acceptance of the apparatus has been calculated using the uniform vertex distributions in longitudinal and transverse position (Figs. 2 and 3), and assuming azimuthal symmetry of the muon angular distribution; it remains substantial ($\geq 10\%$) out to 380 mrad for events occurring in segments 5–12 of the calorimeter (and out to 600 mrad for interactions in the first section of the iron magnet which we also observe). Observe that the raw ratio of events without and with muons is higher outside the horizontal-vertical fiducial boundary (Fig. 3) than it is inside, which is consistent with the calculated dependence of the geometrical acceptance on vertex position. Furthermore, the muon detection efficiency has been obtained from two independent Monte Carlo calculations, which assume scale invariance and form factors consistent with low-energy neutrino data[4] and electroproduction data.[5] These calculations are in agreement with the measured muon angular distribution and other properties of events with muons, as reported previously.[1]

The numbers of events with and without observed muons, before and after correction for muon detection efficiency, are given in Table I. We divide the events into four sets according to whether the vertex occurs in the first or last half of the target-detector at each of the two proton energies. The four independent sets of data

TABLE I. Summary of data analysis

Target segments	Proton energy (GeV)	Visible muon events	No visible muon (1)	Undetected muon events (calc)	Excess muonless events (2)	Purity of sample (2)/(1)	Ratio of cross sections, R
1–6	300	52	59	41	18	25%	0.20 ± 0.12
	400	27	23	20	3		0.06 ± 0.14
7–12	300	72	53	28	25	50%	0.25 ± 0.10
	400	21	23	10	13		0.42 ± 0.23
7–12	300 + 400 combined	93	76	38	38	50%	0.29 ± 0.09

give consistent values for R, the corrected ratio of cross sections without and with muons.[6] Since the geometric acceptances of the two halves of the target-detector are substantially different, the internal consistency of the results gives confidence in the calculated correction for unobserved muons. For the combined segments 7–12, we obtain $R = 0.29 \pm 0.09$, where the error is statistical only. We estimate that the uncertainty in R due to a possible systematic error in the calculated detection efficiency is smaller than the statistical error.

The simplest explanation of this result is the existence of a neutral weak current. If so, our measurement is not in disagreement with the Weinberg model,[7] which predicts a value of R between 0.22 and 0.55 for our mixture of ν and $\bar{\nu}$. Muonless events have also been reported in an experiment done at CERN[8] at much lower neutrino energies. However, other origins of the effect we observe cannot as yet be excluded. Among these are (i) a ν_e ($\bar{\nu}_e$) contamination of the ν_μ ($\bar{\nu}_\mu$) beam more than an order of magnitude larger than the 2% estimated; (ii) an anomalous excess of events in the vicinity of $y = E_h/E_\nu \simeq 1$, due, for example, to the production of a new particle, which would substantially affect the correction for undetected muons; (iii) some novel process resulting from a new type of lepton. Any of these phenomena would indicate a new feature of weak interactions.

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Note added in proof.—Further study of the calculated correction for undetected muon events indicates that measurement error in the transverse position of event vertices leads to an uncertainty in the boundary of the fiducial volume, which results in a small reduction of the muon detection efficiency. Reanalysis of the data with this revised detection efficiency yields $R = 0.23 \pm 0.09$. In addition, the entire experiment has been repeated with an appreciably larger muon detection efficiency and a different admixture of neutrinos and antineutrinos. A description of the new experiment and its result will be given soon.

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[2] The energy response of the liquid-scintillator detector is uniform to ±15% over the active area of a segment, and the sensitivity is 50 keV per collected photoelectron. A minimum-ionizing particle is well resolved in each segment. A detailed report on the detector is in preparation.

[3] The visible energy E_{vis} has been measured relative to the energy deposition of a minimum-ionizing particle. Because of scintillator saturation and nuclear-binding losses we expect $E_{vis} \sim 0.7E_h$, where E_h is the energy of the final-state hadrons.

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