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F. Messing, R. L. Piccioni, J. Pilcher*,
D. D. Reeder, C. Rubbia, R. Stefanski and
L. Sulak

Department of Physics, Harvard University**
Cambridge, Massachusetts

Department of Physics, University of Pennsylvania**
Philadelphia, Pennsylvania

Department of Physics, University of Wisconsin**
Madison, Wisconsin

National Accelerator Laboratory
Batavia, Illinois

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Department of Physics, Harvard University^{**}

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ABSTRACT

We report here 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 study¹ 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, $\nu_\mu(\bar{\nu}_\mu) + \text{nucleon} \rightarrow \mu^-(\mu^+) + \text{hadrons}$, 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 set-up is shown in Fig. 1a. The light from each of the 16 segments of the target-detector was collected to generate a pulse proportional to the energy deposited in each segment². The 16 signals were combined to generate an event trigger whenever the total visible energy³ E_{vis} exceeded a specified 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 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. 1a).

The vertex of the primary interaction was determined by the distribution of the energy depositions in the target and by extrapolation of the spark chamber tracks. The fine 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 vertex reconstruction.

Results are based on 1116 triggers at $E_p = 300$ GeV and 368 triggers at 400 GeV. No trigger within the cosmic-ray gate had a clear vertex within or just outside the target volume. Triggers within the beam gate with a good vertex divide into two groups depending on whether or not counter A fired.

As Fig. 2a shows, the majority of events with a pulse in A have vertices upstream of the target. The vertices of those events occurring inside the target are attenuated in 1.5 target segments, about one 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. 2b) 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. Any hadrons entering from the sides would have a transverse attenuation length equal to one 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 with a r.m.s. deviation of 25 mrad. The absence of any substantial enhancement near the edges of the target therefore demonstrates that there is no appreciable background of hadrons penetrating from the sides.

To ensure good containment of the hadronic cascade, reasonable muon detection efficiency, and rejection of possible hadrons incident from the sides, fiducial volume cuts are imposed: the vertex must occur within the first 12 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 96 at 400 GeV.

The presence of an associated muon in the spectrometer was identified independently a count in C or D or by observation of a track in at least SC5. The only correction is for wide-angle muons which miss the muon identifier. The experimental angular distribution of muons has been directly measured using an enlarged event sample in which are combined the events produced in the first block of iron with events produced in the liquid scintillator target. The geometric acceptance of the apparatus has been evaluated by a

calculation using the observed spatial distribution of events and azimuthal symmetry of the initial angular distribution muons. The geometric acceptance remains substantial ($\geq 10\%$) out to 0.6 rad. The results after correction for geometric acceptance are shown as the histogram in Fig. 4a. Furthermore, two independent Monte Carlo calculations, which assume scale invariance and form factors consistent with low-energy neutrino⁴ data, are in good agreement with this angular distribution (Fig. 4a) and other⁵ observations of muonic events (e.g., Fig. 4b). Calculations are not particularly sensitive to the neutrino spectrum or other input parameters.

We analyze the data in three different ways, each with progressively fewer events as a trade-off against significantly smaller background subtractions. For each analysis, we tabulate (Table I) the observed numbers of events with and without a visible muon, and the calculated number of undetected muon events (UNE). To evaluate the statistical significance of each sample, we display the probability that the observed number of events with no visible muon is a fluctuation from the expected number of UNE. Interpreting the excess of muonless events as a new phenomenon, we characterize it by the quantity R , the ratio between the production cross-sections for muonless and muon events⁶.

(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 give consistent values for the ratio R . Since the angular acceptances of the two halves of the target are substantially different, the agreement between the results gives confidence in the correction for UNE. For the combined segments 7-12 data, we obtain $R = 0.29 \pm 0.09$, where the error quoted is statistical only. If the total number of events with no visible muon is a statistical fluctuation,

it is 5.2 standard deviations from UME.

(II) An improved rejection against UME is obtained by requirements on the angle of the tracks in the double-gap chamber closest to the event vertex. We demand that all observed tracks coming from the primary vertex extrapolate through C and SC5. To avoid pairing ambiguities (stereo angle $= 12^\circ$, and average spark multiplicity ≈ 8), we impose this angle criterion only in the plane observed by one of the cameras. Calculated contributions to UME are (i) 8 muons which would have been observed using the criterion on the projected angle except for excessively large muon angles or spark chamber inefficiency⁷, and (ii) 16 muons missing the detector in the unobserved (horizontal) plane. The probability that a normal distribution with a mean value of 24 and r.m.s. deviation of 5.9 would give 54 observed events corresponds to a fluctuation of 5.1 standard deviations. If this is a new phenomenon, $R = 0.29 \pm 0.10$.

(II) Finally, we retain only those events which satisfy the angular requirement in both horizontal and vertical planes. We expect⁷ 1.9 ± 0.5 UME, arising only from (i), and observe 11 events with no visible muon. The probability of such a fluctuation is 6.7 s.d., and $R = 0.39 \pm 0.19$.

Consistency between the various values of R, in spite of the largely different corrections, gives confidence in the subtraction procedure. Distributions of events along the neutrino beam direction, after correction for muon escape, remain uniform. Hadron energy, hadron angle, shower multiplicity and the vertex location within the target are indistinguishable for events with and without muons. Furthermore, R is insensitive to the cuts on E_{vis} and on fiducial volume.

The simplest explanation of this result is the existence of a neutral weak current. If so, our measurement is in good agreement with the Weinberg

model⁸, which predicts a value of R between 0.25 and 0.55 for our $\nu, \bar{\nu}$ mixture. Upper limits on $\bar{\nu}_e$ -scattering⁴ further constrain R between 0.3 and 0.5. Other origins of the effect we observe cannot as yet be excluded. Among these are (i) more than an order of magnitude larger $\nu_e(\bar{\nu}_e)$ contamination of the $\nu_\mu(\bar{\nu}_\mu)$ beam above the 2% calculated; (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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FOOTNOTES AND REFERENCES

- * Alfred P. Sloan Foundation Fellow, now at the University of Chicago, Chicago, Illinois 60637.
- ** Supported in part by the U. S. Atomic Energy Commission.
- 1 A. Benvenuti et al., Phys. Rev. Letters 30, 1084 (1973).
- 2 The energy response of the liquid scintillator detector is uniform to $\pm 15\%$ 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 technical 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. Due to scintillator saturation and nuclear binding losses we expect $E_{\text{vis}} \sim 0.7 E_h$, the energy of the final-state hadrons.
- 4 D. H. Perkins, Proc. of the 16th Int. Conf. on High-Energy Physics, Batavia, 1972 (NAL Chicago-Batavia, 1972), Vol. 4, p. 189.
- 5 The detailed results of our study of "ordinary" events in which a muon is observed will be reported in a subsequent paper.
- 6 The ratio R is averaged for neutrino and antineutrino contributions in which the final muons are in the ratio $\mu^+ / (-^+ + \mu^-) = 0.19 \pm 0.05$.
- 7 The probability for an unrecorded track has been determined to be 2.5% for observed multiplicities up to 12 and angles up to 0.65 radians from the events themselves, assuming that gaps have independent efficiencies. Above 0.65 radians the efficiency could not be measured for lack of events, and it has been conservatively set to zero; it is this latter condition that dominates UME. Hence raising the inefficiency from 2.5% to the single gap value of 15%

mildly affects the results, rising UME's by 3.0 and 1 event in analysis (II) and (III) respectively.

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TABLE I. Summary of analyses. (I) Analysis of totality of events (II) Analysis with angular requirements in one plane (III) Analysis with angular requirements in both planes

Target segments	Proton energy (GeV)	Visible muon events	No visible muon (1)	UME	Excess muonless events (2)	Purity of sample (2)/(1)	Statistical significance of effect s.dev.	Ratio of cross-sections R
I 1-6	300	52	59	41	18	25%	2.1	0.20 ± 0.12
	400	27	23	20	3		0.5	0.06 ± 0.14
	7-12	72	53	28	25	50%	4.0	0.25 ± 0.10
		21	23	10	13		3.3	0.42 ± 0.23
	7-12	300 + 400 combined	93	76	38	50%	5.2	0.29 ± 0.09
II 1-12	300	56	54	24	30	56%	5.1	0.29 ± 0.10
III 1-12	300	13	11	1.9	9.1	83%	6.7	0.39 ± 0.19

Figure captions:

- 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 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 cross-hatched bins contain all events with a vertex upstream of the detector. (b) Events that did not fire A.
- Fig. 3 Distribution of event vertices in the plane perpendicular to the beam. Full dots depict events with a muon and empty dots 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.
- Fig. 4 (a) Angular distribution of muonic events from the first block of iron and the calorimeter. The distribution shown has been corrected by the geometric acceptance of C and SC5, which is indicated by the dashed line. No events are observed above 0.35 radians. The smooth line shows the results of a full Monte Carlo calculation.

(b) Momentum distribution of all muonic events. A calculation of the full Monte Carlo program (the smooth line) fits the data well. The range cut-off due to the first block of iron is 1.1 GeV.

(a) TARGET SEGMENT NUMBER

(b)