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EXPERIMENT AT FERMILAB

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Talk Presented By
M. Shaevitz
at the
XX International Conference on High Energy Physics
University of Wisconsin-Madison, July 1980

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Talk presented by M. H. Shaevitz at the SLAC Summer Institute on
Particle Physics (August 6-8, 1980).

ABSTRACT

Preliminary results from a new high-statistics study of neutrino
and antineutrino interactions are presented. The full data sample
includes 130,000 charged-current neutrino and 23,000 antineutrino
events detected in the large-acceptance Lab E neutrino target at
Fermilab with the N-30 dichromatic beam. Results based on a pre-
liminary sample of one-third of the data are given for normalized
cross sections, neutral currents, and like-sign dimuons.

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INTRODUCTION

Deep inelastic neutrino scattering has long been a source of information concerning not only the weak interaction itself but also important details of nucleon structure, and more recently, new flavor production. Over the past five years, the experiments built to study these processes have become much larger, yielding increased data samples for analysis. With these new data, the errors have become dominated by systematic rather than statistical errors. In this paper, we report preliminary results from a new high-statistics experiment to measure neutrino interactions with good understanding of systematic effects.

DETECTOR

The Lab E neutrino detector is a separated-function device with a 690 ton target-calorimeter and 420 ton muon spectrometer (Figure 1). The target is composed of non-magnetized steel with transverse dimensions of 3m x 3m and is interspersed with scintillation counters every 10cm of steel and with spark chambers every 20cm. The non-magnetized nature of the target allows the precise tracking of the muon very close to the event vertex giving an angular resolution of

$$\sigma_{\theta}^{\text{Proj}}(\text{mrad}) = .14 + 57/P(\text{GeV}).$$

The muon spectrometer is made of solid iron toroids 12 feet in diameter with spark chambers and scintillation counters every 32" and 8" of steel respectively. The total field of the spectrometer corresponds to a $P_{\perp}$ kick of 2.4 GeV. Figure 2 shows a computer reconstruction of a typical event with a muon traversing the spectrometer.

Absolute calibrations of the energy scale for the calorimeter and muon spectrometer have been performed using momentum-tagged hadron and muon beams coming into Lab E. The resolutions obtained in these cali-

Figure 1: Lab E Neutrino Detector

Figure 2: Computer reconstruction of a typical charged current event.

brations are

$$\Delta P_{\mu} / P_{\mu} = (.114^2 + (8.33 \times 10^{-5} P(\text{GeV}))^2)^{1/2}$$

and

$$\Delta E_H / E_H = .89 / (E_H)^{1/2}$$

NEUTRINO BEAM AND FLUX MONITORING

The experiment uses the new N-30 dichromatic train at Fermilab. In this setup (Figure 3), a 400 GeV primary proton beam impinges on a BeO target, secondary particles are momentum and sign selected and then directed into a 340m evacuated decay pipe. The neutrino detector is located in Lab E, 910 meters downstream. The flux and energy spectrum of neutrinos at the detector is calculated from measurements of the number of pions and kaons in the decay pipe along with their energies and spatial distribution.

A combination of detectors is used to measure the flux of secondaries. The total flux (independent of particle type) is measured by ion chambers placed at two locations along the decay pipe. Each measuring station has three independent ion chamber gaps that allow cross checks to be made throughout the running period. The chambers are connected to the ADC's with sensitivities of either 20pC/count or 200pC/count. The calibration of the ADC's is continuously monitored by inducing pulses of known charge into the units.

The absolute calibration of the ion chambers is measured in two separate ways. First, the response of the chamber to a primary proton beam transported through the train is calibrated against a beam current transformer and RF cavity using a set of foil activation measurements as intermediate monitors. These measurements use a Cu foil of known thickness exposed to the primary proton beam. Although the foil

Figure 3: Layout of the Fermilab dichromatic neutrino beam line.

activation is only used to calibrate the ion chamber against the other devices, we do obtain the activation cross section as a by-product. The value of the cross section measured in this way for Na^{24} in Cu with incident 200 GeV protons is $3.90 \pm .13$ mb which agrees with previous measurements by our group. In the second method, we calibrate the ion chamber directly with a low intensity secondary beam and single particle counting. The calibration from this technique agrees with the first method to 3%. For the results presented in this paper, we estimate the total error for the ion chamber calibration including systematic errors to be 3.5%.

Particle fractions are measured with a differential Cerenkov counter using a He radiator; electronics integrate the counters response over the entire beam spill. The counter has been calibrated by using a mono-energetic 200 GeV primary proton beam coming directly from the accelerator. This calibration provides a measurement of the gas index of refraction to better than .1% and also maps the counter response to a mono-energetic beam. The particle fractions measured with this counter at the different secondary momentum settings used in the experiment are given in Table I.

The flux monitoring system is designed to have many cross checks for the study of systematic errors. A segmented ion chamber (the "muon chamber") behind the beam dump (see Figure 3) measures the number and spatial distribution of decay muons and, therefore, the neutrino flux. At present this device has not been absolutely calibrated and can only be used to check the relative flux between different momenta and polarities. The pion fluxes obtained with this chamber agree with the above measurements using the Cerenkov counter and ion chamber to better than one percent for negative settings and five percent for positives.

TABLE I: Particle Ratios from Cerenkov Measurements

Beam Momentum (Positives)	K/ π	π /P	Beam Momentum (Negatives)	K/ π
			-250	.035 $\pm .002$
+200	.145 $\pm .010$	.224 $\pm .016$	-200	.048 $\pm .003$
+169	.135 $\pm .009$	.403 $\pm .028$	-169	.062 $\pm .004$
+140	.128 $\pm .009$	.640 $\pm .045$	-140	.073 $\pm .005$
+120	.109 $\pm .008$	.895 $\pm .063$	-120	.080 $\pm .006$

For the preliminary results presented here, we estimate the systematic error in the neutrino flux to be below 10%. In the future, we should eventually reach errors of 2-3% with the additional information available from an absolute calibration of the muon chamber and the RF cavity placed in the decay pipe.

Knowledge of the energy spectrum of secondaries in the decay pipe is crucial for inferring the energy and flux of neutrinos at the detector. From measurements of particle yields for pions, kaons, and protons, energy spectra for each of the momentum settings are calculated. These spectra can be checked in two ways. First, for protons and kaons, the mean pressure observed in the Cerenkov counter is related to the mean momentum by

$$\text{Mean} \left(\frac{1}{(\text{Momentum})^2} \right) = \left(\frac{m_K^2 \text{ or } P}{\langle \theta_c^2 \rangle - 2K \langle P \rangle} \right)^{-1}$$

where K and $\langle \theta_c^2 \rangle$ are measured with the 200 GeV mono-energetic proton beam calibration and $\langle P \rangle$ is the mean pressure. With this procedure, the energy can be measured to better than 1% and agrees with the value predicted from the particle yields at that level. An additional check using the measured energy of observed neutrino events also shows agreement to 1%.

TOTAL CROSS SECTION RESULTS

Neutrino and antineutrino data were recorded at five secondary energies (250, 200, 169, 140, and 120 GeV) over a period of eight months ending January 1980. The total sample includes 130,000 charged current neutrino interactions and 23,000 antineutrinos. The cross section results shown here are preliminary and correspond to about one-third of the above sample. All events are reconstructed by computer with fiducial and reconstruction cuts applied to limit the sample to regions with good acceptance and small background. With these cuts, the fiducial volume is restricted to 430 tons. Corrections are made for wide band background, cosmic ray contamination (1%), geometrical efficiency, and the unsampled region at high x and high y (3%). Geometrical inefficiency is corrected by a model independent method in which observed events are weighted by an efficiency factor. The efficiency factor is calculated by rotating the observed event around the beam direction as well as translating the event vertex along the beam direction and determining if the event would be accepted with the new vertex and orientation.

The method for extracting cross sections from the data uses both the events with the muon traversing the toroidal spectrometer (muon trigger events) and events where the muon stops or exits the side of the target before entering the spectrometer (hadron trigger events). The hadronic energy is measured for both types of events but the muon energy (and, thus, the total energy) is only measured for muon trigger events. Once the events are separated into interactions of neutrinos from either pion or kaon decay, the total energy for each event can be determined from its interaction point in the target due to the nature of the dichromatic beam. The separation of events into pion and kaon neutrinos is straightforward for both classes of events. For the muon trigger events, the total energy is measured and can be used for the separation. For hadron trigger events which occur at high y , the hadronic energy for kaon and pion neutrino interactions is sufficiently different to allow separation. With the events separated into radial bins and neutrino types, total cross sections for each beam setting are formed using the neutrino energy and flux distributions described previously.

For the final results shown in Figure 4, the different energy settings are combined; checks made in regions where different settings overlap show the cross sections to agree within statistical errors. The average total cross sections for the range from 40-200 GeV are:

$$\begin{aligned}\sigma_T^{\nu}/E_{\nu} &= .733 \pm .005 \pm .073 \times 10^{-38} \text{ cm}^2/\text{GeV} \\ \sigma_T^{\bar{\nu}}/E_{\bar{\nu}} &= .371 \pm .004 \pm .037 \times 10^{-38} \text{ cm}^2/\text{GeV}\end{aligned}$$

where the first error is statistical and the second systematic. The results agree with our previous measurement¹ for neutrinos of $(.700 \pm .015 \pm .035)$ taken with this beam and detector but are 15-20% higher compared to the world average of $.63 \pm .02$ for neutrinos and $.30 \pm .01$ for antineutrinos.

Figure 4: Total Cross Sections vs. Energy. Upper points are for incident neutrinos; lower points for antineutrinos.

NEUTRAL CURRENTS AND $\sin^2\theta_w$

The most precise measurements of $\sin^2\theta_w$ are from high statistics studies of deep inelastic neutrino scattering. The errors in these measurements are dominated by systematic uncertainties. Experimentally, large background subtractions are necessary to correct for wide band events, charged current events identified as neutral currents, and electron neutrino contamination in the beam. Theoretically, if one extracts $\sin^2\theta_w$ from the ratio of neutral to charged currents, corrections must be applied for scaling violations, anti-quarks, neutron-proton excess, and the experimental cut on the minimum detectable hadronic energy. We have chosen to measure $\sin^2\theta_w$ from the data by using the Paschos-Wolfenstein relations² with additional kinematic cuts in an effort to minimize some of the above uncertainties. In this method,

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho \left(\frac{1}{2} - \sin^2\theta_w \right)$$

and

$$R^+ = \frac{\sigma_{NC}^{\nu} + \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} + \sigma_{CC}^{\bar{\nu}}} = \rho \left(\frac{1}{2} - \sin^2\theta_w + \frac{10}{9} \sin^4\theta_w \right)$$

These relations are true independent of any details of scaling violations or amount of anti-quark contribution and, thus, eliminate some theoretical corrections inherent in the simple ratio method.

Experimentally, this method demands that neutrinos and antineutrinos be normalized relative to one another and that the target nucleus be isoscalar; both requirements are satisfied by this experiment (small corrections are necessary for the neutron excess in Fe). The ratios, R^+ and R^- are independent of the particular kinematic region used and can,

therefore, be evaluated in a domain where charged and neutral current events are clearly distinguished. The region of confusion is at high x and y where the outgoing muon exits the target before being identified. This region can be eliminated by a cut on $Y_{NC} = (\text{Observed hadron energy}) / (\text{Neutrino energy predicted from the dichromatic beam at the given radius})$. The cut depends on the event radius, r , and the length, L_{cut} , required to identify a muon in the detector and is given by

$$Y_{NC} < Y_{cut} = \frac{E_{\nu} \theta_{\max}^2}{2M_p + E_{\nu} \theta_{\max}^2} \quad \text{where } \theta_{\max} = \tan^{-1} \frac{60'' - r}{L_{cut}}$$

Figure 5 shows a length distribution before and after a Y_{cut} . With an $L_{cut} = 210\text{cm}$, it can be seen that the charged current contamination under the neutral current peak is substantially reduced; moreover, the shape agrees well with the Monte Carlo prediction. With this procedure, the charged current contamination in the neutral current sample is reduced to a 4% for neutrinos and 2% for antineutrinos.

The preliminary results given here are for the 200 GeV momentum setting (about 1/3 of the total data) for neutrinos and antineutrinos from pion decay with $L_{cut} = 210\text{cm}$ and $E_{hadron} > 20\text{ GeV}$. Small corrections as shown in Table II have been applied for the backgrounds mentioned previously giving the results:

$$R^- = .258 \pm .035$$

$$R^+ = .326 \pm .015$$

Additional corrections for strange/charm quarks, charm quark threshold effects, kaon neutrino contamination, and the small excess neutron content of the iron target amount to +3.4% for R^- and +3.9% for R^+ . Converting these ratios to measurements of $\sin^2\theta_w$ gives the results:

Figure 5: Length distribution for neutrino events
 The lower histogram has an additional
 cut on Y_{NC} with $L_{cut} = 210$ cm (see
 text). The curve is a Monte Carlo prediction
 for charged current events with the same cuts.

Two Parameter Fit $\rho = 1.01 \pm .10$

$$\sin^2 \theta_w = .246 \pm .056$$

One Parameter Fit $\sin^2 \theta_w = .239 \pm .023$ with $\rho = 1.0$

TABLE II: Corrections to the Neutral Current Events

	Neutrinos	Antineutrinos
Charged Current Back	-3.9%	-2.0%
Cosmic Rays	-1.0%	-5.3%
Wide Band Background	-1.4%	-0.1%
Ke3 Background	-1.7%	-0.4%
π/K Decay in Shower	+0.1%	+0.1%
Other Corrections	+0.2%	+0.9%
Total	-7.7%	-6.8%

LIKE-SIGN DIMUON PRODUCTION

Over the past few years, several experiments^{3,4,5} have observed the production of neutrino induced like-sign dimuon events at high energy. Two questions have arisen concerning these events. First, are the events associated with a prompt source and not just π/K decay? Second, if the events are prompt, what is the source? For the results presented here, we address these two questions.

The amount of π/K decay contamination in our sample of like-sign dimuon events is calculated using a novel approach which relies on experimental data as much as possible. The calculation separates the

background ~~into~~ into two parts; a contribution from the decay of hadrons produced in the primary neutrino interaction and a contribution from the shower produced when these hadrons interact in the steel. The calculation utilizes a Field-Feynman quark jet simulation program⁶ based on fits to neutrino-induced hadron final state data as measured in Neon bubble chamber experiments. This program provides the multiplicity and energy distributions for hadrons produced in the primary neutrino interaction. The contribution from subsequent interactions of these hadrons is determined using direct measurements of π -Fe interactions from another experiment⁷ where both prompt muon and non-prompt muon rates have been measured at several incident hadron energies. This method uses empirical data except for first-generation decays where it assumes that ν -Ne distributions are the same as the ν -Fe distributions and that the Field-Feynman fits also represent the data at high hadron energies where the bubble chamber data are relatively poor. The procedure has been cross-checked by using new bubble chamber data⁸ at higher energies directly instead of the Field-Feynman program. Figure 6 shows a comparison of these two methods along with the rate for muon production by incident pions. The two calculations agree on the amount of background in the dimuon sample to better than 20% and are close to the rate observed for pionic production

In a previous experiment (Experiment 482 at Fermilab) using the quad-triplet neutrino beam, we observed twelve like-sign events with $P_{\mu} > 9$ GeV and a calculated π/K decay background of 1.3 events. In the present experiment (with about one-third of the data analyzed), we have found nine like-sign events with 2.6 events background. (The difference in the ratio of signal to background for the two experiments is due to

Figure 6: Comparison of the different methods of calculating the π/K decay background. The curves are the probability to produce a μ^- with $P_{\mu^-} > 9 \text{ GeV}$ from π or K decay as a function of the hadronic energy. The solid curve uses the Field-Feynman quark jet program; the dot-dashed uses ν -Ne bubble chamber data directly. The dashed curve is production by incident pions.⁷

the like-sign events produced at neutrino energies above 250 GeV in the quad-triplet beam.) Clearly, a prompt signal of like-sign events is established; the probability that all the like-sign events originate from π/K decay is extremely small. The purity of these two samples is better than previous experiments in which the background is typically as large as the prompt signal. The reduction of the π/K decay background in this experiment is primarily due to the P_μ cut of 9 GeV, the high density of the target, and high energy beam.

Figure 7 shows the opposite- and like-sign rate versus neutrino energy for the two data samples. The event distributions have been corrected for geometrical efficiency and π/K decay background. The opposite-sign events show a sharp rise with energy around 50 GeV and flattening above 100 GeV characteristic of charm quark production convoluted with the experimental acceptance. In contrast, the like-sign events show a strong energy dependence over the entire range from 50-200 GeV. A large rise with energy is expected for the production of heavy mass particles and is most probably enhanced by the P_μ requirement. (A Monte Carlo calculation of $C\bar{C}$ production gives correction factors for the P_μ cut of 5 and 2 for $E_\nu = 100$ and 200 GeV respectively.) A theoretical curve based on a first order QCD calculation of charm-anti-charm production via gluon bremsstrahlung and including experimental acceptance is also shown in Figure 7. The curve does show a large rise with energy but lies about two orders of magnitude below the observed data. There is an expectation that higher order corrections will raise this calculated rate substantially⁹. For this reason, $C\bar{C}$ production is still a possible source of the like-sign events.

Table III gives the average kinematic variables for the opposite- and like-sign samples. Several features are evident. The average ϕ

Figure 7: The prompt opposite- and like-sign dimuon rate with $P_\mu > 9$ GeV versus energy. The curve is a QCD calculation of $C\bar{C}$ production with the second muon from the $\bar{C}$ decay.

TABLE III - Average Quantities for $\mu^-\mu^+$ and $\mu^-\mu^-$ Events

	This Exp. $\mu^-\mu^+$	This Exp. $\mu^-\mu^-$	Exp. 482 $\mu^-\mu^+$	Exp. 482 $\mu^-\mu^-$
E _{vis} (GeV)	166 ± 5	154 ± 4	148 ± 6	179 ± 19
E _h (GeV)	76 ± 2	77 ± 4	62 ± 4	101 ± 14
P _{μ2} (GeV)	23 ± 2	16 ± 1	19 ± 1	14 ± 2
P _{⊥2} ^S (GeV)	.61 ± .05	.50 ± .04	.91 ± .07	.63 ± .14
φ (deg)	140 ± 4	135 ± 4	130 ± 5	131 ± 8
x _{vis}	.16 ± .02	.24 ± .03	.14 ± .01	.22 ± .07
y _{vis}	.61 ± .03	.60 ± .02	.59 ± .02	.63 ± .05
z _μ	.27 ± .02	.18 ± .02	.33 ± .02	.17 ± .04
W (GeV)	12.0 ± .3	10.8 ± .3	11.3 ± .4	12.7 ± 1.2

where

$$E_{vis} = E_{\mu 1} + E_{\mu 2} + E_h$$

P_{μ2} is the momentum of the second muon

P_{⊥2}^S is the momentum of the second muon perpendicular to the
hadron shower direction

$$x_{vis} = 2E_{\mu 1} E_{vis} \sin^2(\theta_{\mu 1/2}) / (E_{\mu 2} + E_h)M_P$$

$$y_{vis} = (E_h + E_{\mu 2}) / E_{vis}$$

$$z_{\mu} = P_{\mu 2} / (P_{\mu 2} + E_h)$$

W is the invariant mass of the hadron system

angle and hadron energy, E_h , indicate that like-sign events are associated with the hadron vertex and, therefore, exclude heavy leptons as the source. The value for P_{12}^S is smaller for the $\mu^-\mu^-$ sample compared to the $\mu^-\mu^+$ sample; this quantity should be larger if the $\mu^-\mu^-$ events are from the direct decay of quarks heavier than charm (bottom, top, etc.). The average z_μ for like-sign events is about one half the value for opposite-sign events as would be expected for $C\bar{C}$ production where the C and $\bar{C}$ quarks share the gluon energy. In general, the kinematic distributions of the like-sign events are consistent with the source being the hadronic vertex, and specifically from the decay of a charmed particle in associated production.

In conclusion, we have observed a large rate for the production of like-sign dimuons by neutrinos at high energy. Calculations indicate that the background from π/K decay is very small. The like-sign rate shows a steep rise with energy consistent with the production of a heavy mass state. While the source of the like-sign dimuons is still not known, it is not likely that they originate from either heavy leptons or quarks heavier than charm. Associated charm-anticharm production is one possible source that cannot be ruled out. Further studies with higher energies and statistics should help clarify this question.

Reprints Removed

REFERENCES

1. J. Lee, California Institute of Technology, Thesis (unpublished).
2. E. A. Paschos and L. Wolfenstein, Phys. Rev. D7, 91, (1973).
P. Q. Hung and J. J. Sukurai, Phys. Lett. 63B, 292, (1976).
3. A. Benvenuti et al., Phys. Rev. Lett. 41, 725, (1978).
4. M. Holder et al., Phys. Lett. 70B, 396, (1977).
5. J. G. H. deGroot et al., Phys. Lett. 86B, 103, (1979).
6. R. Field, private communications.
7. Data of Fermilab Experiment 379.
8. I. S. Chima, private communications, ν -Ne data from the BEBC collaboration.
9. G. L. Kane et al., Phys. Rev. D. 19, 1978, (1979).