A STUDY OF THE WEAK NEUTRAL CURRENT E-594

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"Everything in nature is lyrical in its ideal essence; tragic in its fate, and comic in its existence."

- George Santayana

Introduction

In the Standard Model of electroweak interactions, neutrinos scatter off the quarks inside the nucleon by one of two mechanisms: the charged-current interaction, or the neutral-current interaction. The charged-current interaction proceeds by the exchange of a $W^{\pm}$ boson, thereby transforming the incident-muon neutrino into a muon and altering the flavor of the target quark. The neutral-current interaction is mediated by the neutral Z^0 boson, and leaves the identity of the incident neutrino and the flavor of the target quark intact. Figure 1 is a schematic representation of these two neutrino-nucleon interactions.

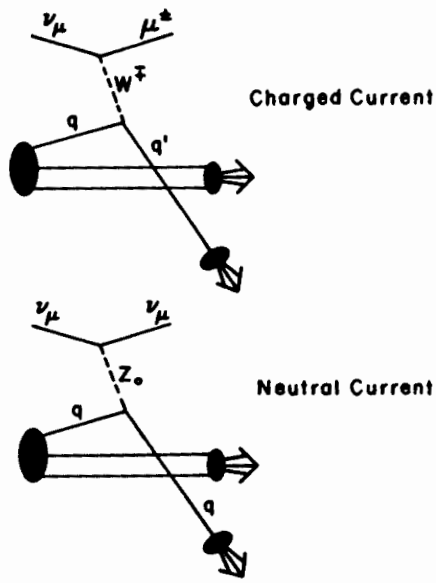

Figure 1. The Feynman diagrams for (a) the charged-current interaction and (b) the neutral-current interaction.

An experiment here at Fermilab, E-594, is in the final stages of analysis on a comparison of these two neutrino interactions. An analysis of our data has recently been published where we searched for deviations from the predictions of the Standard Model. Certain questions can be confronted with the data. Is the quark sea inside the nucleon the same in the neutral-current interaction as it is in the charged-current interaction? Are there any exotic objects in the nucleon which seem to couple preferentially to the neutral current?

We have also made a measurement of the neutrino-nucleon total cross section, searched for neutrino-flavor oscillations, estimated the mean-parton transverse momentum inside the nucleon, and checked the V-A theory of the charged-current interaction by the means of inverse-muon decay.

The experimental team was a collaboration between Fermilab, the Massachusetts Institute of Technology, and Michigan State University. The people involved were: D. Bogert, R. Burnstein, R. Fisk, S. Fuess, J. G. Morfin, T. Osaka, L. Stutte, J. K. Walker; J. Bofill, W. Busza, T. Eldridge, J. I. Friedman, M. C. Goodman, H. W. Kendall, I. G. Kostoulos, T. Lyons, R. Magahiz, T. Mattison, A. Mukherjee, L. Osborne, R. Pitt, L. Rosenson, A. Sandacz, M. Tartaglia, F. E. Taylor, R. Verdier, S. Whitaker, G. P. Yeh; M. Abolins, R. Brock, A. Cohen, J. Erwein, D. Owen, J. Slate, and H. Weerts.

The Experimental Technique

The study of the weak neutral current presents several experimental challenges. The key difficulties are the separation of the neutral-current interaction from the charged-current interaction and the reconstruction of the kinematics of neutral-current scattering. The solution to both of these problems is to sample the reaction products of the neutrino-nucleon interaction in very fine steps. This enables the two interaction types to be separated, and the angle and energy of the recoil hadron shower to be measured. By taking data in a narrow-band neutrino beam where the incident-neutrino energy can be inferred, the full kinematics of both the neutral-current and the charged-current events can be reconstructed.

Other benefits of building a fine-grained detector are that rare event topologies, e.g., inverse-muon decay, and quasi-elastic scattering, can be studied. Electron showers can be separated from hadron showers. In addition, certain details of deep-inelastic scattering events are accessible, such as the angle between the lepton-scattering plane and the hadron-shower plane.

Figure 2 shows a plan view of the neutrino detector used in E-594. The apparatus is based on plastic flash chambers and proportional wire chambers. Most of the mass of the detector is

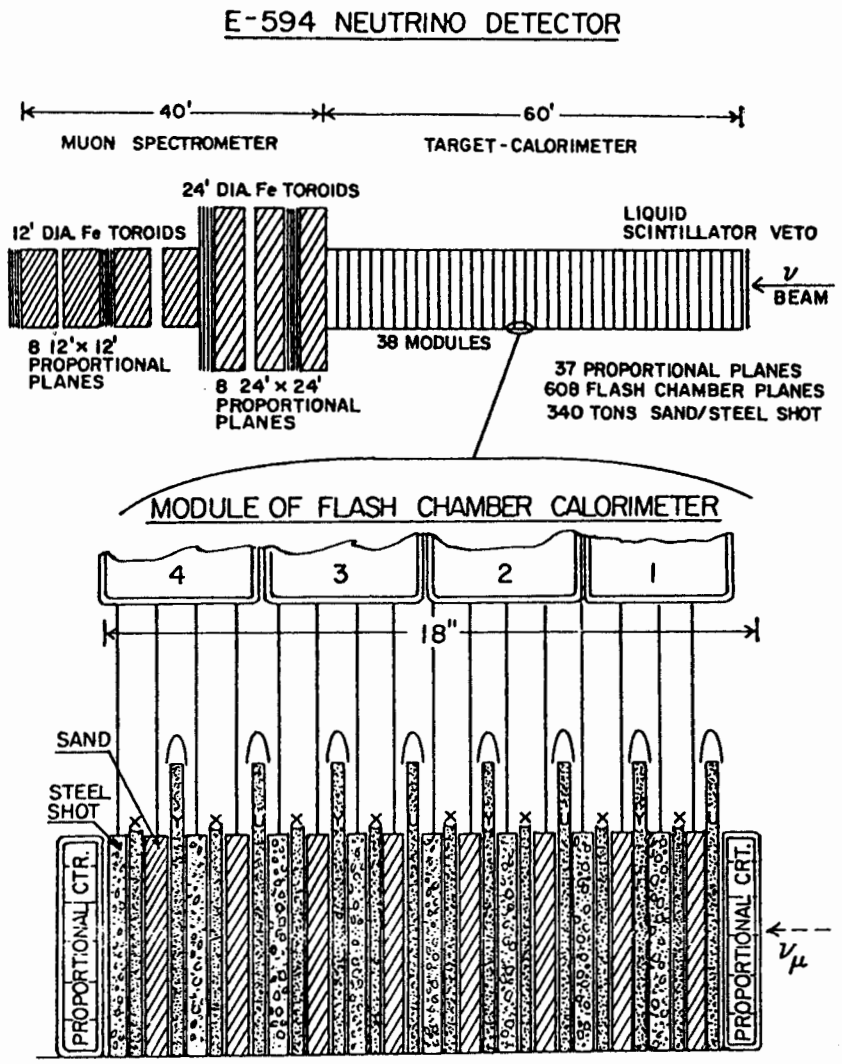

Figure 2. The E-594 detector is shown in plan view. The mass of the calorimeter is about 340 metric tons. The iron toroids measure the momentum of the muons from charged-current interactions.

in thin plastic sheets filled with either sand or steel shot. The detector is unique in that it samples the shower every 22% of a radiation length and every 3% of an absorption length, which is a finer-grained sampling than any other electronic neutrino detector.

The Neutral Current Nucleon Structure Functions

The experiment recorded 12,400 neutrino interactions after acceptance cuts in data taken in the narrow-band neutrino beam. The kinematical variables of the neutral-current and the charged-current scattering have been reconstructed by using the observed energies and angles of the recoil hadron showers. To reduce the systematics of the neutral-current/charged-current comparison, we presented our result as a ratio of the respective x distributions of the two interactions. (The variable x is the Bjorken scaling variable which is given by $x = Q^2/2M_p\nu$ and is a measure of the ratio of the momentum of the struck quark to that of the target nucleon.)

The comparison of the neutral-current and the charged-current x distributions is shown in Fig. 3. The charged-current data have been normalized to the same number of events as the neutral-current data at each momentum setting of the narrow-band train to make the comparison of the two distributions more direct.

The neutral-current/charged-current ratio as a function of x is shown in Fig. 4. All of the neutrino data have been combined, since there is no systematic difference between the various momentum settings. The figure indicates that the x dependence of the ratio is essentially flat, implying that the nucleon structures probed in the two interactions are the same as expected by the Standard Model. Detailed fits have been made to these ratios and they indicate no systematic difference between the two interactions.

Work is in progress to actually determine the structure functions themselves by deconvoluting the resolution smearing. This will be complementary to the ratio comparison described above.

Determination of $\sin^2\theta_W$

The strength of the weak neutral current depends on the quark electric charge, the quark weak isospin, and on the free parameter $\sin^2\theta_W$. Deep-inelastic neutrino-nucleon scattering offers the most statistically potent data from which to determine $\sin^2\theta_W$. To exploit this statistical power, it is necessary to minimize the theoretical and experimental systematic uncertainties of the determination. This requires knowledge of the quark structure of the nucleon, and the neutral-current and charged-current events must be well separated. The nucleon structure complications have been tested in our determination of the neutral-current structure functions described above, and the fine granularity of the neutrino detector allows the two event types to be distinguished with small corrections on an event-by-event basis.

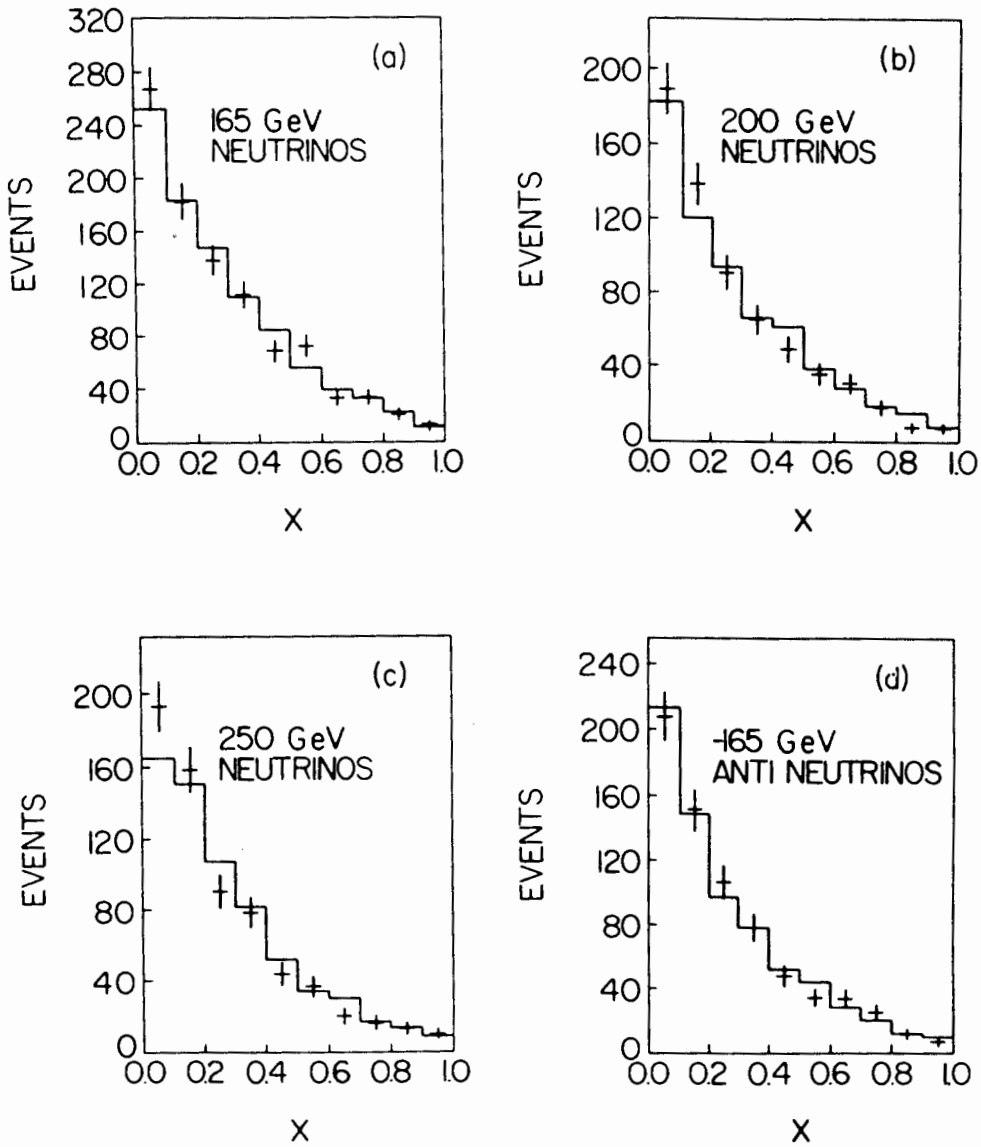

Figure 3. The neutral-current and charged-current x distributions at the four beam settings of the experiment. The neutral-current data are indicated by the error bars and the charged-current data by the histogram.

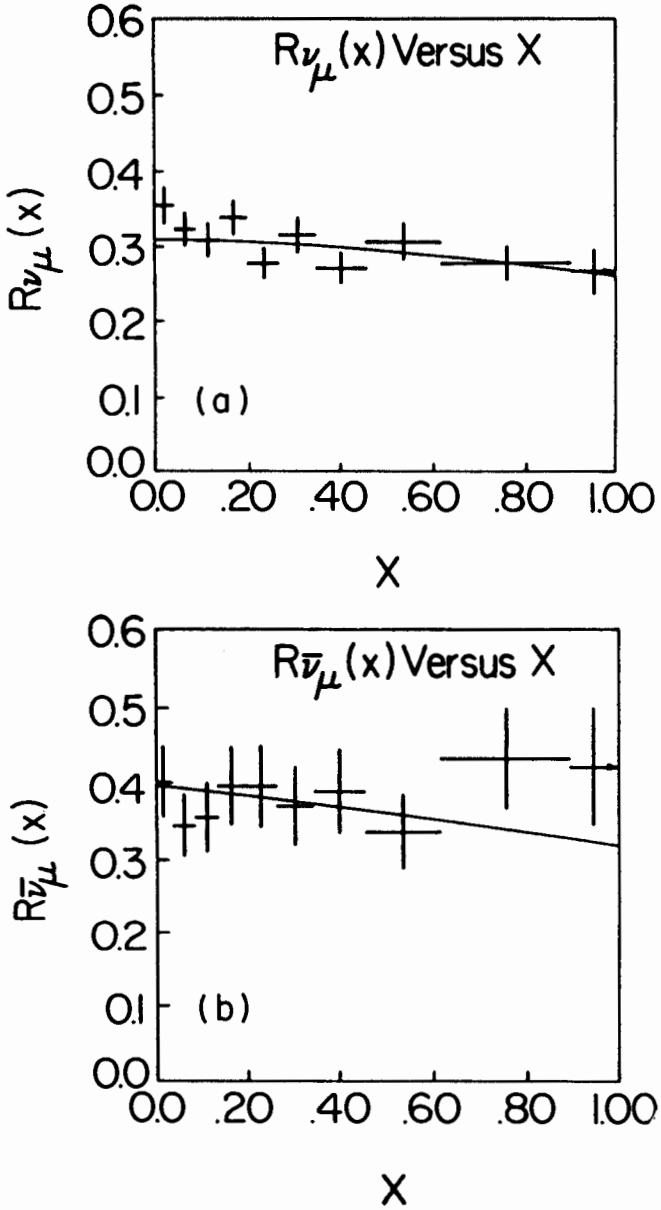

Figure 4. The neutral-current to charged-current ratio as a function of x for (a) neutrinos, and (b) antineutrinos. The solid line indicates the result of a fit to the neutral-current structure functions.

The value of $\sin^2\theta_W$ was extracted from the data by using the ratio of the total number of neutral-current events which satisfy certain experimental cuts to the corresponding number of charged-current events. This ratio is computed for both neutrinos and antineutrinos and is shown in Fig. 5. The line is the expectation of the Standard Model as a function of $\sin^2\theta_W$. We obtained

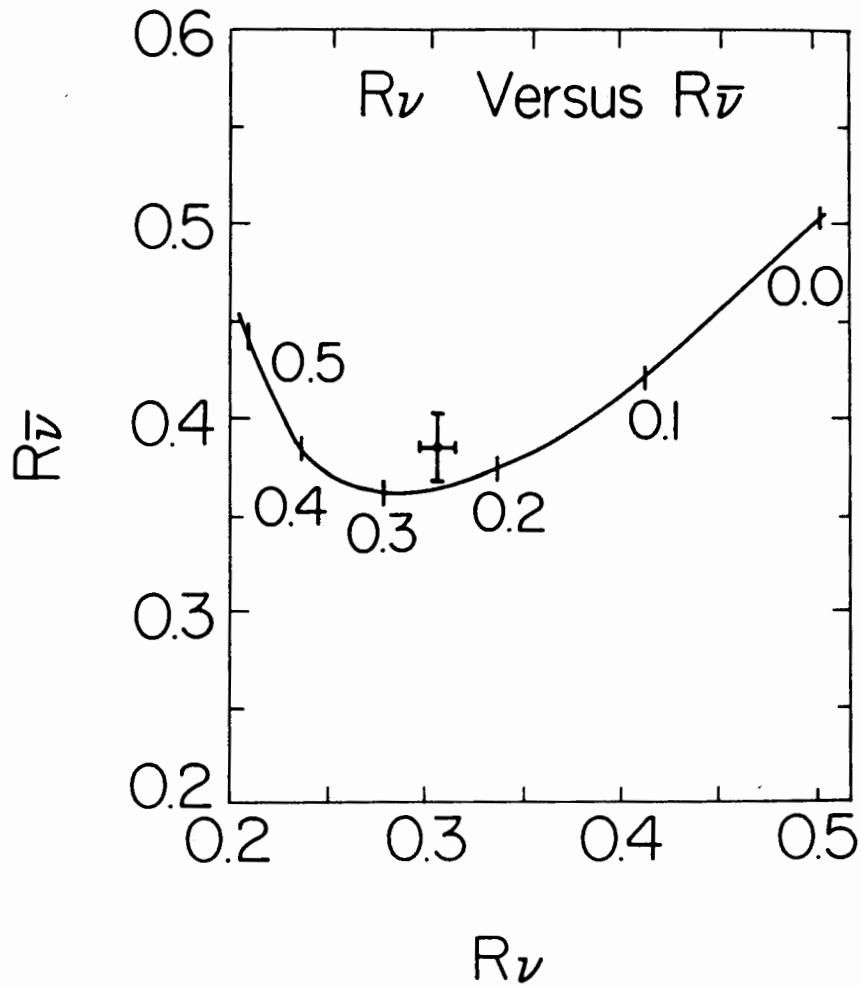

Figure 5. The neutral-current to charged-current ratio for antineutrinos is plotted against the corresponding ratio for neutrinos. The line is the expectation of the Standard Model as a function of $\sin^2\theta_W$.

the value $\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013$, where the first error is statistical and the second is an estimate of systematic effects. This number is in agreement with other determinations both here at Fermilab and at other labs.

The extraction of $\sin^2\theta_W$ depended on small effects in the charged-current cross section. In particular, it was sensitive to the amount of the strange sea and to the mass of the charmed quark.

Measurement of the Total Cross Section

The narrow-band beam technique allows the incident-neutrino flux to be measured by monitoring the beam of the pions and kaons which decay to produce the neutrino beam. By measuring the ratio of observed events in the neutrino detector divided by the inferred neutrino-beam flux the total neutrino cross section can be determined. Our preliminary value for incident neutrinos is given by

$$(\sigma_T/E)_\nu = (0.613 \pm 0.007 \pm 0.031) \times 10^{-38} cm^2/GeV$$

and for the antineutrino beam by,

$$(\sigma_T/E)_{\bar{\nu}} = (0.332 \pm 0.009 \pm 0.022) \times 10^{-38} cm^2/GeV.$$

The first error is the statistical error and the second estimates systematic effects. Further checks and refinements of these numbers will be done, but at present they are equal within errors to the earlier determinations.

Search for Neutrino Oscillations

We have searched for neutrino oscillations in the narrow-band beam where we hypothesize that the original muon-neutrino beam oscillates into tau neutrinos. The search exploited the energy constraints afforded by the narrow-band beam and the ability of our detector to reconstruct quasi-elastic events.

The energy of the outgoing muon will essentially equal the energy of the narrow-band beam in muon-neutrino quasi-elastic scattering. In tau quasi-elastic scattering, the outgoing-tau energy is again constrained to be nearly equal to the incident-neutrino energy, but only a portion of the energy is observable, since the tau decays into a muon and two unobserved neutrinos. By selecting events with the quasi-elastic signature, but with a muon energy less than the narrow-band neutrino energy, an oscillation limit can be computed. The result expressed in terms of the mass difference parameter Δm^2 at maximal neutrino flavor mixing at the 90% confidence level upper limit is $\Delta m^2 < 8\ eV^2$ for incident neutrinos and $\Delta m^2 < 7\ eV^2$ incident antineutrinos.

These results are comparable with other determinations (within a factor of 3) and present another way of searching for the oscillation effect in a simple scattering channel.

Other Analysis Projects

Other analyses near completion are a study of the transverse momentum of the quarks inside the nucleon, and a check of the V-A structure of the inverse-muon decay.

The mean-parton transverse momentum has been estimated by the distribution of the angle between the hadron plane and the lepton-scattering plane in charged-current events. We can determine the lepton-scattering plane from the incident-neutrino beam direction and the outgoing-muon track. The hadron plane is estimated by the pattern of energy deposition in the flash chambers. The cosine of this angle will have a small but finite average arising from the energy dependence of the neutrino-parton cross section and geometric factors expressing the incident-neutrino energy in the parton-rest frame. The preliminary value of the parton-transverse momentum is $\langle p_T \rangle = 0.35 \pm 0.10$ GeV/c, where the error is statistical only.

Inverse-muon decay is a beautiful reaction where a muon-neutrino scatters off an electron, giving a muon and an electron neutrino. The reaction involves only leptons and can proceed by only the charged-current interaction. Thus, it is a nice test of the V-A theory. The chief difficulty is that the cross section is tiny. Nevertheless, we have observed a few of these events in the narrow-band beam and have been able to test the theory. The ratio of theory to data, assuming the standard V-A structure for charged-current events, is given by $S = 1.00 \pm 0.28$ verifying that pure V-A is a good model. Our result confirms the earlier measurements at CERN.

Future Program

We are anticipating that the sequel experiment to E-594 (E-649) will carry these studies to the uniquely high energies produced by the new narrow-band beam operating at the Tevatron. The energy constraints of the narrow-band beam and our fine-grained calorimeter will allow several incisive studies of neutrino physics in a new high-energy regime. The collaboration has recently taken data in the wide-band beam at the Tevatron (E-733) to study the dimuon production process, and to look at deep-inelastic neutrino-nucleon scattering at high energies. These data will nicely complement the narrow-band program of E-594 and E-649.