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Measurement of the Cross Section for $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

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A total of ~ 249 000 neutrino interactions were observed at Fermilab in a high-angular-resolution electromagnetic shower detector, with ~ 0.947×10^{19} protons of 350-GeV energy incident upon the production target. Based on a data sample of 0.71×10^{19} protons, 46 electrons were observed with $\theta_e \leq 10$ mrad. Of these 46 events, 34 are attributed to the process $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, and 12 are attributed to background processes. This leads to the following results: $\sigma = (1.40 \pm 0.30)\times 10^{-42} E_\nu$ cm^2 and $\sin^2\theta_W = 0.25^{+0.07}_{-0.05}$.

Since the discovery in 1973 of weak neutral-current interactions,[1] efforts have been made to determine the nature of the weak-coupling constants[2] and to compare them with the predictions of the gauge theories of Weinberg and Salam.[3] To date, the most accurate measurements have involved hadronic currents as well as leptonic currents, and have been in overall good agreement with the Weinberg-Salam (WS), and the Glashow-Iliopoulos-Maiani (GIM) theory.[4] Measurements of purely leptonic processes, such as

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-, \quad (1)$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-, \quad (2)$$

$$\nu_e + e^- \rightarrow \nu_e + e^-, \quad (3)$$

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-, \quad (4)$$

have been limited by statistics, resulting in less conclusive evidence for agreement with the WS theory. In principle, these purely leptonic processes should provide better tests of weak-interaction theories. The theoretical estimates are precise in these cases because the complications due to hadronic attributes are not involved.

In this paper, we report on the results of an experiment to measure the cross section of reaction (1) with substantially better statistics than previously reported.

The experiment was conducted in the single-horn focused, wide-band ν_μ beam, at the Fermi National Accelerator Laboratory. The average neutrino energy was about 20 GeV and extended to over 100 GeV. The beam contamination was estimated to be ~11% for ν_μ, and less than 0.5% for both ν_e and $\bar{\nu}_e$. Approximately 0.947×10^{19} protons (~1.5 C) at 350 GeV were delivered onto the pion production target.

The apparatus was located ~500 m from the end of the pion-decay pipe. It consisted mainly of 49 basic modules of detectors. Each module, with details shown in Fig. 1, was made of one 9.27-cm-thick aluminum plate (~1 radiation length), one 1-m×1-m multiple-wire proportional chamber filled with an 80% argon, 19.7% CO_2, and 0.3% Freon-13-B1 mixture, and one layer of plastic scintillation counters. The cathode planes of each chamber consisted of copper-clad G-10 boards, milled into a delay-line configuration of spacing 1.5 mm. The x and y coordinates of the edges of showers were measured in each chamber with five taps equidistantly spaced across each of two orthogonal edges of the chamber. The signal from each of the taps was fed to a time-to-digital

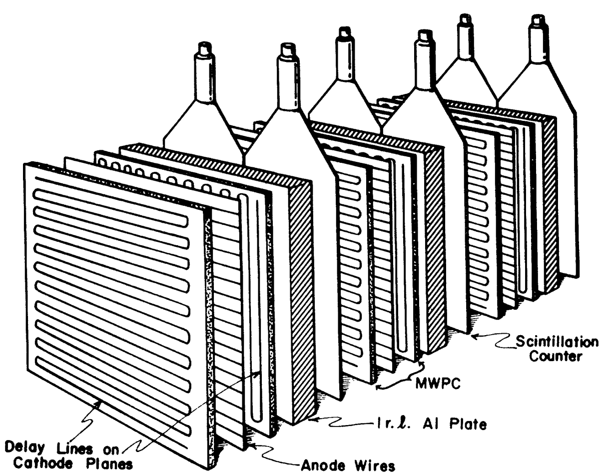

FIG. 1. Schematic showing the details of a basic detector module.

converter (TDC) to record the distance from a tap as a time interval. Anode wires of each chamber were grouped together and their common pulses were fed to an analog-to-digital converter (ADC) to record energy deposited in the chamber. Details of the chamber construction and performance will be published elsewhere.[5] The plastic scintillation counters in each module were also used to record the energy deposited in that layer. Hodoscope counters (A) before the apparatus were used to reject muons while, behind the apparatus, two banks of hodoscope counters (B and C), separated by ~4′ of steel, identified charged-current interaction events by the muon penetration.

The trigger for an event was given by $\bar{A}\cdot(\text{CH})\cdot S$, where $\bar{A}$ was the front charged-particle veto, CH was the analog pulse-height sum of any six consecutive chambers, and S was the logical pulse sum of any four consecutive layers of scintillation counters. Typically, about 2 GeV of shower energy was needed to be deposited in order to trigger.

A portion of the apparatus consisting of 5 modules was tested using 2.5–9.5-GeV electrons at Cornell University, and a 10-module section for 5–30-GeV electrons and pions at Fermilab. The results of these tests indicated an angular resolution of ±5 mrad (full width at half maximum) at 4 GeV, and little energy dependence. The tests also gave an absolute energy calibration and yielded detailed information of longitudinal and lateral shower development of electrons and pions. Electron showers in the first few radiation lengths would typically be less than 10 cm in diameter with centroids determined to about 8 mm on the average. The energy resolution for detecting electrons is typically $\lesssim\pm8\%$ depending upon the electron energy.

A total of ~249 000 triggers were taken during the run. Because of low discriminator settings and high-beam rates, an average deadtime of 33% was observed.

About 70% of the 249 000 triggers have been scanned, each one by a physicist using a computerized visual display. Those events in which a shower was observed without an outgoing muon were retained for further analysis. Muon-induced events and those obviously coming from outside of the detector assembly were rejected. For each of the accepted events, a single shower was assumed. The two "outer edges" of the shower in each chamber were determined, using the redundancy of the TDC information. The midpoint of the edges was then assumed to be the centroid of the shower in that chamber. A straight-line fit to the centroids of the first five chambers of an event for both x and y coordinates was then made. Because most of these events are due to neutral-current interactions and involve more than one electromagnetic shower, only about one-third of the events could be fitted. For those events for which straight-line fits could be made, only those events with at least one projected angle less than 50 mrad were retained. Each event was then examined and fitted again by a physicist, resulting in a reduction to ~480 events. After application of a dE/dx cut to separate electrons from pions,[6] a final sample of 313 events was obtained. Various distributions were examined for possible biases, such as the vertex distribution through the detector volume. In order to clearly identify the events, only 40 detector modules and a fiducial area of 90 cm×90 cm transverse to the beam direction were used in the final selection. Figure 2 shows the visible electron energy distribution for those events with $\theta_e \leq 10$ mrad as well as the expected distribution for the assumed neutrino spectrum and $\sin^2\theta_W = 0.25$. Agreement is quite good and indicates no obvious energy-dependent biases.

Figure 3 shows the observed angular distributions for those events satisfying either $\theta_x \leq 50$ mrad or $\theta_y \leq 50$ mrad. As can be seen, there is a significant concentration of events for angles less than 10 mrad. We ascribe these events to process (1), consistent with $\nu_\mu e$ kinematics, and previously mentioned angular resolution of the apparatus. To further test this hypothesis, the kinematically limiting invariant quantity, $E_e\theta^2 = 2m_e \simeq 1$ MeV, is plotted in Figs. 4(a)–4(c). With an experimental resolution of approximately ± 5 mrad, and an average electron energy of ~15 GeV, one should expect about $\frac{2}{3}$ of the true $\nu_\mu e$ events to satisfy this condition. The bulk of the events with $\theta \leq 10$ mrad is consistent with this expectation.

The true number of $\nu_\mu e$ events can be obtained from any of three plots: the E-θ^2 scatter plot with $\theta \leq 10$ mrad, the $dN/d\Omega$ plot with $\theta \leq 10$ mrad, and the $E\theta^2$ plots with $\theta \leq 10$ mrad and $10 < \theta \leq 20$ mrad. Using the various plots, we have calculated that 46 events are observed for 0.71×10^{19} protons incident upon the neutrino production target. These 46 events are separable into 34 events for process (1), and 12 events mainly due to background processes. Using the relative fluxes of ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$, we calculate that ~6 of background events are due to[7] $\nu_e + n \to e^- + p$; and attribute the other 6 events to neutral-current interactions. The relatively large contribution of the former reaction arises from the form factors in the scattering. The overall detection efficiency for $\nu_\mu e$ events is 54%, taking into account the fiducial-volume cut and equipment deadtime.

To calculate the cross section for Reaction (1), it is necessary to determine the incident neutrino flux. Due to the fact that the apparatus did not contain a magnet to measure muon energy, total visible energy of charged-current events could not be used to determine the neutrino energy spectrum. To obtain the latter, we used the measured hadronic energy spectra of the charged current events in a fiducial volume of 20 cm×20

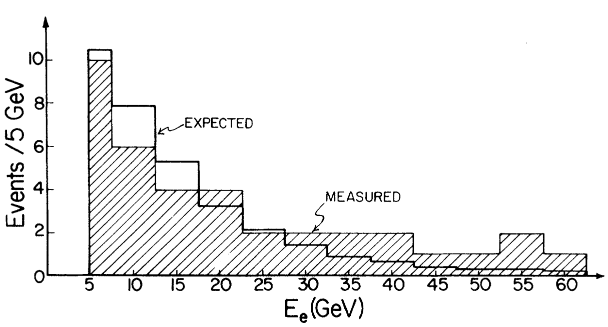

FIG. 2. Visible electron energy spectrum for events with $\theta_e \leq 10$ mrad. The expected event numbers were computed by assuming $\sin^2\theta_W = 0.25$ and folding in the assumed neutrino spectrum experimental detection efficiency and energy resolution.

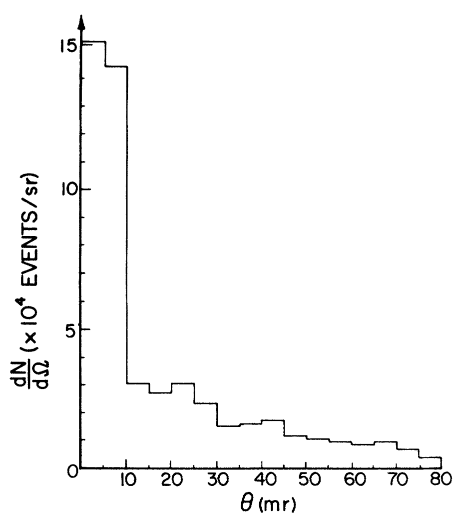

FIG. 3. Angular distribution of measured events per unit solid angle which satisfies either $\theta_x \leq 50$ mrad or $\theta_y \leq 50$ mrad.

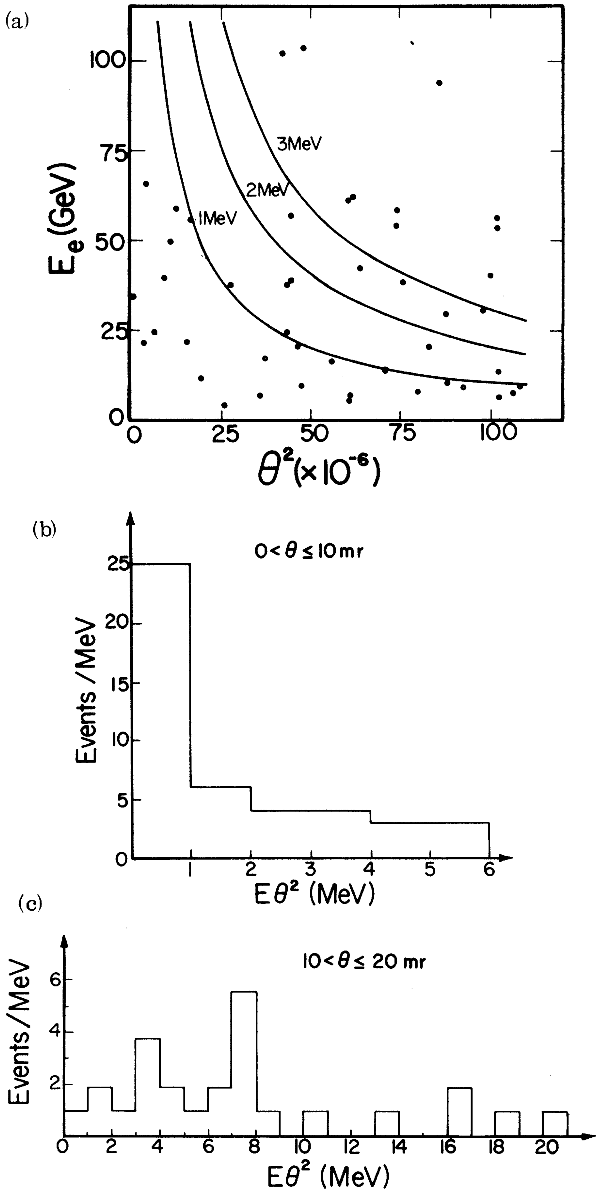

FIG. 4. (a) Distribution of observed $\nu_\mu e$ candidates with $\theta \leq 10$ mrad in the E-θ^2 plane. (b) $E\theta^2$ distribution of observed events in the angular range of $\theta \leq 10$ mrad. (c) $E\theta^2$ distribution of observed events in the angular range of $10 < \theta \leq 20$ mrad.

cm×40 layers and compared that to the expected distribution using a Monte Carlo calculation and various assumptions as to the magnitude and shape of the incident-neutrino-energy spectrum.

In the Weinberg-Salam theory, the cross section for $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ is given by[8]

$$\frac{d\sigma}{dy} = \frac{G_V{}^2 m_e E_\nu}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2(1-y)^2\right],$$

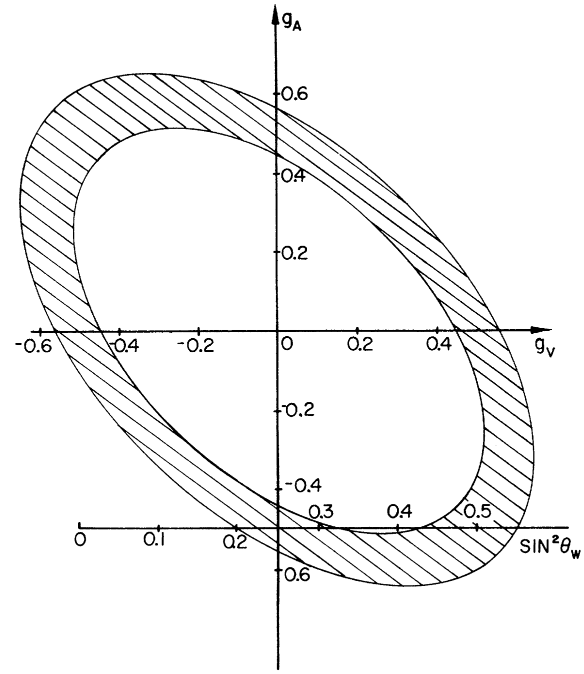

FIG. 5. The shaded elliptical area corresponds to the region allowed by the cross section measured in this experiment, $(1.40 \pm 0.30)\times 10^{-42} E_\nu$ cm^2. The left intersection it makes with the theoretical line of $g_A = -\frac{1}{2}$ yields the value $\sin^2\theta_W = 0.25^{+0.07}_{-0.05}$.

where $G_V \simeq 1.02\times 10^{-5}/M^2{}_p$, the Fermi coupling constant; g_V and g_A, the vector and the axial-vector coupling constant between leptons; and $y = E_e/E_\nu$. We have integrated this expression, using limits for y indicated by $E_e \geq 4$ GeV. The corrected total cross section for the reaction $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ then becomes $(1.40 \pm 0.30)\times 10^{-42} E_\nu$ cm^2, which yields a value for $\sin^2\theta_W = 0.25^{+0.07}_{-0.05}$ that agrees well with the world average of 0.232 ± 0.009.[2] The corresponding coupling constants are given by $g_V = 0.00^{+0.14}_{-0.10}$ and $g_A = -0.50 \pm 0.06$. The errors quoted here are only statistical. There could be systematic errors mainly due to uncertainties in the neutrino-flux calculation. By several considerations of the flux normalization, we ascribe a systematic error of $\pm 0.2 \times 10^{-42} E_\nu$ cm^2 in the cross section and about 0.04 in uncertainty in $\sin^2\theta_W$.

Figure 5 shows the ellipse of our measurement in the g_V-g_A plane. The determination of $\sin^2\theta_W$ is helped by the predictions of the Weinberg-Salam model; namely, $g_A = -\frac{1}{2}$ and $g_V = 2\sin^2\theta_W - \frac{1}{2}$. Since there are two intersections between the experimental ellipse and the theoretical line of $g_A = -\frac{1}{2}$ in the g_V-g_A plane, the ambiguity is removed by utilizing results from measurements such as deep-inelastic νN or $\bar{\nu}N$ scattering, elastic νp scattering, single-pion production by neutrinos[2], and scattering of polarized electrons from a deuterium target.[9] The good agreement of $\sin^2\theta_W$, measured in this experiment, with those most precisely determined in νN scattering by Holder *et al.*,[10] and in polarized eD scattering,[9] demonstrates similarities of the couplings for νe, νq, and eq, where q indicates the quark. This gives strong support to the WS-GIM theory. Also, it provides a positive test of the idea of factorization in neutral-current interactions.[11]

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