Measurement of the Ratio of Cross Sections for Neutrino and Antineutrino Scattering from Electrons

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Measurements of the ratio R of the purely leptonic weak neutral-current cross sections $\sigma(\nu_\mu e \rightarrow \nu_\mu e)/\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)$ and of the absolute value of $\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)$ are reported. These yield $R = 1.38^{+0.40}_{-0.31}(\text{stat}) \pm 0.17(\text{syst})$ and $\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)/E_{\bar{\nu}_\mu} = [1.16 \pm 0.20(\text{stat}) \pm 0.14(\text{syst})] \times 10^{-42}$ cm^2/GeV. This value of R determines the fundamental weak neutral-current parameter to be $\sin^2\theta_W = 0.209 \pm 0.029(\text{stat}) \pm 0.013(\text{syst})$.

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In the standard electroweak model,[1] $SU(2)_L \times U(1)$, the ratio of the cross sections of the purely leptonic weak neutral-current reactions

$$\nu_\mu e \rightarrow \nu_\mu e \tag{1}$$

and

$$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e \tag{2}$$

is completely prescribed by

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3\,\frac{1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W}{1 - 4\sin^2\theta_W + 16\sin^4\theta_W}, \tag{3}$$

which depends only on $\sin^2\theta_W$, the fundamental weak neutral-current parameter. A measurement of R, which we report in this paper, yields a significantly more precise determination of $\sin^2\theta_W$ than do the absolute cross sections measured singly. This is due to the functional relationship between R and $\sin^2\theta_W$ in Eq. (3), and to the fact that, in first order, certain systematic errors in the analysis of the data of reactions (1) and (2) and in their absolute normalization cancel in the ratio. The resulting determination of $\sin^2\theta_W$ is consequently limited primarily by the numbers of events of reactions (1) and (2) that are observed, and not by either systematic or theoretical uncertainties.

This paper is based on a study of interactions produced by ν_μ ($\bar{\nu}_\mu$) of mean energy 1.5 (1.4) GeV at the Brookhaven alternating-gradient synchrotron (AGS), and observed in a massive, high-resolution detector target. The detector target[3] was designed specifically to measure the elastic scattering reactions (1) and (2), and ν_μ ($\bar{\nu}_\mu$) $+ p \rightarrow \nu_\mu$ ($\bar{\nu}_\mu$) $+ p$, as well as the quasielastic processes $\nu_\mu n \rightarrow \mu^- p$ and $\bar{\nu}_\mu p \rightarrow \mu^+ n$. It possesses time resolution of ± 2 nsec, and energy and angular resolutions for electromagnetic showers of $\Delta E_e/E_e = 0.12/E_e^{1/2}$, and $\Delta\theta = 16\ \text{mrad}/E_e^{1/2}$, with E_e measured in gigaelectronvolts.

The data presented here were obtained from exposures of 0.88×10^{19} and 3.4×10^{19} protons on the AGS neutrino-producing target for reactions (1) and (2), respectively. A measurement of the $\nu_\mu e \rightarrow \nu_\mu e$ absolute cross section from these data was presented in an earlier report.[3a] Treatment of the $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ data is essentially similar to that of the $\nu_\mu e \rightarrow \nu_\mu e$ data, but a brief description of the $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ analysis is given here to clarify certain differences in detail.

The $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ event sample was extracted by subjecting the data from 2.4×10^6 AGS beam bursts to a loose software filter designed to eliminate wide-angle events (> 200 mrad) and events which did not exhibit an electromagnetic shower. The resulting sample (1.37×10^5 events) was then double scanned by physicists to eliminate events which the filter did not remove, such as those with an interacting hadron, or with more than one associated electromagnetic shower, or with an upstream vertex. A test sample for evaluating scanning biases and efficiencies was provided by randomly seeding into the scan Monte Carlo–generated $\bar{\nu}_\mu e$ events overlaid with detector noise obtained from actual data. After the eye scan a sample of 3356 events remained. Further reduction in the sample was provided by removing events with more than 30 MeV extra energy at the origin, or with more than 2.5% of the shower energy outside wide limits consistent with multiple scattering and shower development. The resulting sample of clean, isolated, electromagnetic showers contained 735 events within a fiducial volume of $3.5\times3.5\times15.8$ m^3 and with $210 < E_e < 2100$ MeV.

Backgrounds to the $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ signal consist of (1) photons from π^0 mesons produced in neutral-current reactions, (2) electrons from $\bar{\nu}_e p \to e^+ n$ induced by $\bar{\nu}_e$ contamination in the beam, and (3) a small component of misidentified low-energy hadrons. The photon background is measured directly by use of the fact that the energy deposition for electron- and photon-induced showers is markedly different in the first radiation length. Imposing a cut on the ionization loss in the first two proportional drift tube planes and the first calorimeter plane after the vertex[3a] yields a sample of primarily singly ionizing events in which approximately 91% of the $\bar{\nu}_\mu e$ electrons are retained and only about 35% of the photons are included. A second sample predominantly containing photons remains.

Guided by the kinematic condition $E_e\theta_e^2 = 2m_e(1 - E_e/E_\nu)$ we plot the θ_e^2 distribution for the two samples in Fig. 1. A clear signal peak at small θ_e^2 upon an approximately flat distribution is visible in the sample containing dominantly electrons [Fig. 1(a)], while the distribution of the mainly photon sample is seen to be without significant small-angle enhancement. Approximately 96% of the signal is expected within $\theta_e^2 < 0.01$ rad^2. Figures 1(c) and 1(d) show the corresponding distributions for the $\nu_\mu e$ data.[3a] In Fig. 2 are plots of $E_e\theta_e^2$ for $\bar{\nu}_\mu e$ and $\nu_\mu e$ to exhibit the degree to which the data satisfy the kinematic condition above.

To extract the number of events in the signal region, $\theta_e^2 < 0.01$ rad^2, we have determined the backgrounds in the region $0.01 < \theta_e^2 < 0.03$ rad^2 and extrapolated them into the signal region. Each background is approximately flat as a function of θ_e^2 in the forward angular region $\theta_e^2 < 0.03$ rad^2 and thus may be simply extrapolated into the signal region with small uncertainty. The fraction of photons in the signal region (38% of the total background in that region) is calculated directly from the electron-photon selection process. The remaining background in the signal region is attributable to $\bar{\nu}_e p \to e^+ n$ (44%) and to low-energy hadrons that scatter inelastically or are attended by small showers (18%). The $\bar{\nu}_e p \to e^+ n$ component was obtained from a Monte Carlo calculation that satisfactorily describes data[4] on $\nu_e n \to e^- p$ extracted from the same exposure as the data of reaction (1). After background subtraction, which was done fitting the θ_e^2 distribution to the sum of the background components (taking the photon and low-energy hadron distributions as flat) and the expected shape of reaction (2) including angular resolution, a signal of 59 ± 10 events remains. This signal is then corrected for loss of events due to the event selection criteria and limited acceptance described above. The correction factors are summarized in Table I.

To determine the cross sections $\sigma(\bar{\nu}_\mu e)$ and $\sigma(\nu_\mu e)$ and their ratio, we have indirectly measured the integrated incident neutrino fluxes using samples of quasielastic events, $\bar{\nu}_\mu p \to \mu^+ n$ and $\nu_\mu n \to \mu^- p$, with small momentum transfers, $0 < Q^2 < 0.4$ GeV^2.

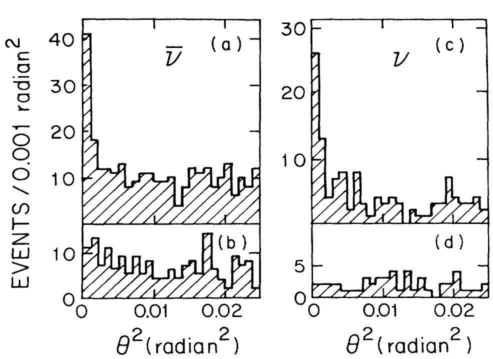

FIG. 1. Distributions in θ_e^2 for (a) the primarily singly ionizing events from the $\bar{\nu}_\mu$ data and (b) the predominantly photon sample from the $\bar{\nu}_\mu$ data. (c),(d) The corresponding plots for the ν_μ-induced data.

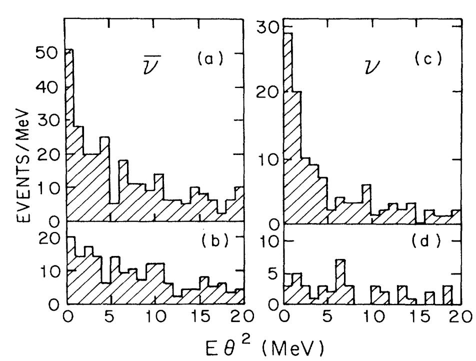

FIG. 2. Distributions in $E_e\theta_e^2$ for the same event samples as in the corresponding plots of Fig. 1.

TABLE I. Corrections applied to $\bar{\nu}_\mu e$ signal and $\mu^+ n$ normalizing events to obtain

$$\frac{\sigma(\bar{\nu}_\mu e)}{E_{\bar{\nu}_\mu}} = \frac{N^e_{\rm obs}}{N^\mu_{\rm obs}} \frac{A_{\rm QE}}{A_e} \frac{\epsilon_{\rm QE}}{\epsilon^e_1 \epsilon^e_2} \frac{1}{(1-B_{\rm QE})} \frac{\langle \sigma^{\bar{\nu}}_{\rm QE} \rangle}{\langle E_{\bar{\nu}_\mu} \rangle}.$$

$N^e_{\rm obs}$ [a]		52.5 ± 8.9 ± 2.1
Acceptance of energy cut	A_e	0.710 ± 0.010
Eye-scan and filter efficiency	ϵ^e_1	0.888 ± 0.019
Combined $\bar{\nu}_\mu e$ cut efficiency[b]	ϵ^e_2	0.823 ± 0.033
$N^\mu_{\rm obs}$ [a] (including the sample correction)		91 700 ± 499 ± 2043
Acceptance for quasielastic events	$A_{\rm QE}$	0.294 ± 0.008
Ratio of flux averaged cross section and energy (10^{-38} cm^2/GeV)	$\langle \sigma^{\bar{\nu}}_{\rm QE} \rangle / \langle E_{\bar{\nu}_\mu} \rangle$	0.291 ± 0.014
Track reconstruction and event selection	$\epsilon_{\rm QE}$	0.864 ± 0.060
Fractional background from single and multipion channels	$B_{\rm QE}$	0.298 ± 0.034

[a] A correction has been made to $N^e_{\rm obs}$ and $N^\mu_{\rm obs}$ for events produced by a measured (7 ± 2)% contamination of ν_μ in the $\bar{\nu}_\mu$ beam. The contribution to the overall systematic error on $\sigma(\bar{\nu}_\mu e)/E_{\bar{\nu}_\mu}$ from this correction is less than 2%.

[b] This takes into account event losses arising from shower energy containment, electron-photon separation, limit on the extra energy at the event vertex, and angle reconstruction.

Random sampling was employed to extract a subset of forward-going muons from the same data samples that yielded the $\bar{\nu}_\mu e$ and $\nu_\mu e$ events. These events were selected by requiring only that the outgoing muon angle with respect to the incident neutrino beam be less than 260 mrad, and that the muon kinetic energy be greater than 0.3 GeV. Events with a visible second track were rejected but no other requirement was placed on the recoiling hadron. Samples of 3.38×10^4 $\mu^+ n$ and 6.02×10^3 $\mu^- p$ candidates were obtained.

Backgrounds in the normalization samples arise from the presence of charged-current soft single-pion and multipion events. In the $\mu^+ n$ sample single-pion production constitutes 28% of the total sample, while in the $\mu^- p$ sample the corresponding single-pion channels are 31% of the total sample, after detector acceptance is taken into account. Multipion backgrounds are less than 8% of each of the $\mu^+ n$ and $\mu^- p$ total samples, including acceptance factors. Corrections are made for the single-pion channels which are dominated by $I = \frac{3}{2}$, Δ-resonance production,[5] and for multipion channels, with relatively small uncertainty. A summary of the corrections necessary to determine the absolute number of $\bar{\nu}_\mu p \to \mu^+ n$ events produced is presented in Table I.

Analysis of the $\bar{\nu}_\mu e$ and $\mu^+ n$ data using the expression in Table I yields the total cross section

$$\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e)/E_{\bar{\nu}_\mu} = [1.16 \pm 0.20({\rm stat}) \pm 0.14({\rm syst})] \times 10^{-42}\ {\rm cm^2/GeV}. \quad (4)$$

The systematic error arises largely from the absolute normalization by use of the quasielastic events. It was estimated quantitatively by variations in the factors that determine the corrected electron and muon samples. Effects studied in the normalization included the Fermi momentum distribution, Pauli exclusion, the value of M_A, the scattering and absorption of pions and nucleons internal and external to the target nucleus, and uncertainties in the cross sections for single-pion and multipion production. Contributions to the systematic error from the electron-photon separation, from electron angular resolution, and from other smaller corrections affecting signal extraction were estimated in the same manner.

The fully corrected ratios of the normalized cross sections for $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering yield directly the value

$$R = 1.38^{+0.40}_{-0.31}({\rm stat}) \pm 0.17({\rm syst}). \quad (5)$$

The precision is limited by the numbers of $\bar{\nu}_\mu e$ and $\nu_\mu e$ events. In the calculation of the systematic error on R

TABLE II. Contributions to the error in the $\nu/\bar{\nu}$ flux ratio.

Component	Uncertainty in R
M_A	1%
Flux	
(shape uncertainty)	3%
Acceptances[a]	4%
Uncertainty in single-pion cross section	5%
Uncertainty in multipion cross section and acceptance	5%
Tracking and event-selection efficiency	3%

[a]Includes hadron and pion scattering effects both inside and outside the target nucleus for events occurring on bound targets.

uncertainties in the experimental and theoretical quantities (due to the effects mentioned above) largely cancel. The error on the $\nu/\bar{\nu}$ flux ratio determined from the $\mu^- p/\mu^+ n$ ratio is estimated to be 9%. The individual contributions to this error are summarized in Table II. The contribution to the uncertainty in R from systematic differences in the treatment of the $\nu_\mu e$ and $\bar{\nu}_\mu e$ samples is 8%.[6] The resulting value of $\sin^2\theta_W$ is

$$\sin^2\theta_W = 0.209 \pm 0.029(\text{stat}) \pm 0.013(\text{syst}). \quad (6)$$

Figure 3 shows a plot of R vs $\sin^2\theta_W$.

There is only one previously published measurement of the cross-section ratio,[7] the data from which have been combined with later data from the same group[8] to yield $\sin^2\theta_W = 0.215 \pm 0.032(\text{stat}) \pm 0.013(\text{syst})$. The agreement between the two experiments is good. Together they give a combined value:

$$\sin^2\theta_W(\text{combined}) = 0.212 \pm 0.023. \quad (7)$$

This combined value of $\sin^2\theta_W$ obtained through purely leptonic interactions is in agreement with and approaches in precision the world-average values of $\sin^2\theta_W$ obtained from deep-inelastic lepton-nucleon scattering[9] and the masses of the intermediate vector bosons.[10]

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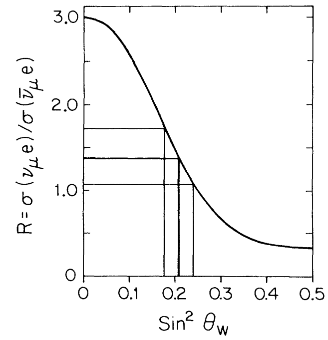

FIG. 3. Plot of $R = \sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$ against $\sin^2\theta_W$. The less heavy lines indicate the standard deviation errors on R and $\sin^2\theta_W$.

(a)Deceased.

(b)Now at National Laboratory for High Energy Physics (KEK), Oho, Tsukuba, Ibaraki-Ken 305, Japan.

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6For the purpose of the present paper the quoted systematic error on R is relatively unimportant compared with the statistical error. This systematic error is dominated by uncertainties in the $\nu_\mu e$ data sample selection. Improved knowledge of the efficiencies of the filter and the eye scan of the $\bar{\nu}_\mu e$ data (analyzed at a later time) have reduced these uncertainties. In due time the ν_μ data (increased by additional events now on tape) will be analyzed as were the $\bar{\nu}_\mu$ data. Hence the systematic error of our final measurement is expected to be dominated by that on the $\mu^- p/\mu^+ n$ ratio.

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