Determination of $\sin^2\theta_W$ and ρ in Deep-Inelastic Neutrino-Nucleon Scattering

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We have determined the electroweak parameters $\sin^2\theta_W$ and ρ by a measurement of deep-inelastic neutrino-nucleon scattering used a fine-grained neutrino detector exposed to a narrow-band neutrino beam at Fermilab. The sampling properties of our detector have permitted neutral-current and charged-current events to be well separated over a wide kinematic range, thereby allowing a determination of $\sin^2\theta_W$ and ρ to be made with good statistics and small systematic errors. We have found $\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013$ in a single-parameter fit.

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In the standard $SU(2) \otimes U(1)$ model of Glashow-Weinberg-Salam[1] all the neutral-current neutrino-quark couplings are determined by the quark weak isospin, the quark electric charge, and the free parameter $\sin^2\theta_W$. In the minimal version of the model, the relative strength, ρ, of the neutral-current (NC) neutrino-quark coupling to that of the charged-current (CC) neutrino-quark coupling is fixed by the relation $\rho = M_W^2/M_{Z^0}^2 \cos\theta_W = 1$, where M_W and M_Z are the $W^\pm$ and Z^0 gauge boson masses, respectively. The model is frequently extended[2] to include a more complicated Higgs structure beyond a single isodoublet, allowing ρ to be different from 1.

Deep-inelastic neutrino-nucleon scattering offers the most statistically potent data from which to determine $\sin^2\theta_W$ and ρ. 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 NC and CC events must be well separated. The nucleon-structure complications can be adequately treated in data taken with an isoscalar target,[3] and our fine-grained neutrino detector allows the two event types to be distinguished with small corrections on an event-by-event basis.

This experiment recorded 12 400 deep-inelastic neutrino interactions, after acceptance cuts, in a 340-metric-ton calorimeter[4] exposed to a narrow-band neutrino beam at Fermilab. Kinematic and fiducial-volume cuts were made to optimize the NC and CC identification, and to minimize background events induced by electron neutrinos arising from K_{e3} decay in the narrow-band parent beam. To reduce the confusion between CC and NC events, we have required the inelasticity $y = (E_h - M)/E_\nu < 0.7$, where E_h is the hadron energy, M is the mass of the nucleon, and E_ν is the energy of the incident neutrino inferred from the energy-versus-angle correlation of the $\pi_{\mu 2}$ decay neutrinos from the narrow-band beam. The hadron energy was required to satisfy $E_h - M > 10$ GeV, so that it is well above the trigger threshold of the calorimeter. The radius of the neutrino-nucleon interaction vertex from the incident-neutrino-beam axis was required to be less than 1 m, making the fiducial mass of the detector 55 metric tons.

We studied our classification uncertainties by performing a complete simulation of the experiment. By analyzing these Monte Carlo events by the same analysis package that was used for the data, we found that 1% of the CC events were misidentified as NC events, and approximately 4% of the NC events were misidentified as CC events. These corrections are the integral corrections averaged over all sources of neutrinos, including the electron neutrinos from K_{e3} decay, and the neutrinos from wide-band backgrounds. The events produced by $K_{\mu 2}$ neutrinos comprised about 11% of the NC and CC $\pi_{\mu 2}$ data sample. The K_{e3} background was roughly 1% of the accepted NC events and the wide-band neutrino background was determined to be about 1% of the accepted NC and CC events.

Data were taken at narrow-band-beam secondary momenta of 165, 200, and 250 GeV/c for neutrino production and 165 GeV/c for antineutrino produc-

TABLE I. The number of accepted events at various beam conditions. P_0 is the central momentum of the narrow-band train. The $(-)$ $+$ momentum settings correspond to (anti)neutrino beams. The mean true neutrino energy, E_ν, and the mean true four-momentum transferred to the struck quark, Q^2, for the experimental cuts of $y < 0.7$ and $E_h - M > 10$ GeV have been estimated by the Monte Carlo simulation of the experiment. The raw and corrected number of accepted events correspond to before and after the event-classification correction, respectively. The errors of $R_{(\bar{\nu})}$ are the statistical uncertainties.

P_0 (GeV/c)	E_ν (GeV)	Q^2 [(GeV/c)^2]	Number of events Raw NC	Raw CC	Corrected NC	Corrected CC	$R_{(\bar{\nu})}$
165	61.3	11.0	950	3235	966	3219	0.300 ± 0.011
200	74.7	12.2	638	2184	647	2175	0.298 ± 0.013
250	92.4	13.8	656	2093	677	2072	0.327 ± 0.014
-165	61.5	8.6	723	1945	740	1928	0.384 ± 0.017

tion. Table I indicates the beam conditions, mean values of several kinematic variables, the raw number of events, and the number of events at each beam setting after corrections were made for the NC-CC separation.

We have used the integral NC-to-CC ratios for both neutrino and antineutrino data to determine $\sin^2\theta_W$ and ρ. These ratios are defined by

$$R_{(\bar{\nu})} = \frac{I(^{(}\bar{\nu}^{)} + N \to {}^{(}\bar{\nu}^{)} + X)}{I(^{(}\bar{\nu}^{)} + N \to \mu^{\pm} + X)}, \quad (1)$$

where $I(^{(}\bar{\nu}^{)} + N \to {}^{(}\bar{\nu}^{)} + X)$ is the accepted number of NC events which satisfy the cuts described above, and $I(^{(}\bar{\nu}^{)} + N \to \mu^{\pm} + X)$ is the corresponding number of accepted CC events. The ratios were calculated separately for all four secondary momentum settings shown in Table I. The neutrino ratios have the greater sensitivity to $\sin^2\theta_W$, while the additional consideration of the antineutrino ratio allows $\sin^2\theta_W$ and ρ to be decoupled partially, and thus to be determined simultaneously.

The extraction of $\sin^2\theta_W$ and ρ in deep-inelastic neutrino scattering is based on the assumption that the quark scaled-momentum distributions in the NC structure functions are the same as those of the CC structure functions. In a separate work[5] we have tested this assumption by showing that there is no significant difference of the nucleon structure measured in the two interactions. Thus, in the present analysis we used the QCD parametrization of the quark distributions given by Duke and Owens[6] for both the NC and the CC structure functions. However, we found that the extracted values of $\sin^2\theta_W$ and ρ were not very sensitive to the detailed Bjorken x dependence of the quark distribution functions as long as the quark x distributions were the same for both the NC and the CC interaction.

To account for the flavor-mixing and heavy-quark effects in our computation of the theoretical CC cross section, we included the Kobayashi-Maskawa mixing-matrix[7] terms, and the so-called slow rescaling terms[8] for charmed-quark production where the charmed-quark mass was taken to be 1.5 GeV/c^2. Radiative corrections along the muon leg have been made,[9,10] and the value of ρ has been modified to correct for the radiative effects from box diagrams.[11] External bremsstrahlung and nonisoscalar[12] corrections for our target material have been found to be negligible.

The measured value of R_ν is plotted against $R_{\bar{\nu}}$ in Fig. 1. We averaged the three neutrino ratios given in

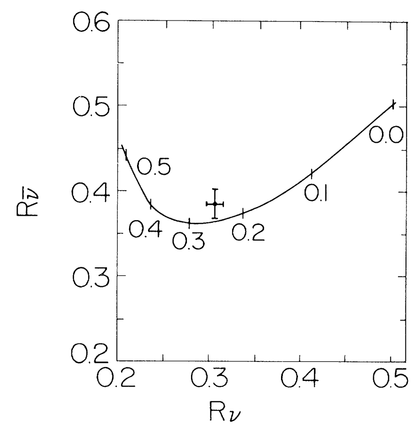

FIG. 1. The average value of the NC/CC ratio R_ν for the three neutrino-beam settings plotted against the value of the NC/CC ratio $R_{\bar{\nu}}$ for antineutrinos. The error bars on R_ν and $R_{\bar{\nu}}$ represent the statistical uncertainties. The curve is the theoretical relation between R_ν and $R_{\bar{\nu}}$ as a function of $\sin^2\theta_W$ with all the radiative effects, slow rescaling corrections, experimental cuts, and resolution smearing described in the text.

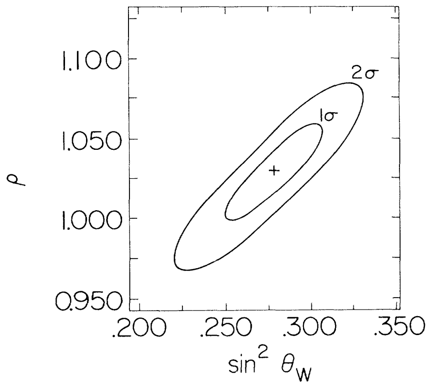

FIG. 2. The 1- and 2-standard-deviation contours (Ref. 13) for the simultaneous fit of $\sin^2\theta_W$ and ρ. The value of ρ has been shifted by the radiative-correction factor discussed in the text.

Table I for the plotted value of R_ν. In this figure we show the prediction of R_ν vs $R_{\bar{\nu}}$ as a function of $\sin^2\theta_W$. The curve was computed with all of the effects mentioned above, as well as the resolutions and cuts of this experiment.

The values of $\sin^2\theta_W$ and ρ were determined by a minimum-χ^2 fitting procedure[13] where all four NC/CC ratios were included as four separate data points. All known details of the incident neutrino beam, the experimental resolutions,[4] the backgrounds, and the experimental cuts were considered. In our fit for $\sin^2\theta_W$ alone we found

$$\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013, \tag{2}$$

where the first error is statistical and the second is systematic. The value of ρ was fixed to 0.9915 for the box-diagram radiative correction.[14] The χ^2/(degrees of freedom) of the fit was 3.9/3. The two-dimensional fit with the muon leg and box-diagram radiative corrections yielded

$$\sin^2\theta_W = 0.279 \pm 0.027 \pm 0.019, \quad \rho = 1.027 \pm 0.023 \pm 0.026. \tag{3}$$

The χ^2/(degrees of freedom) for the fit was 2.5/2. We note that the magnitude of ρ in this fit is consistent with the standard-model value of 1.0. In the two-dimensional fit, the parameters $\sin^2\theta_W$ and ρ are strongly correlated. This is illustrated in Fig. 2.

The systematic errors of these calculations arise from both experimental and theoretical sources and are listed in Table II. The experimental systematic errors for the single-parameter fit are dominated by the NC-CC separation corrections, and the systematic error from theoretical sources arises primarily from the slow rescaling correction in the calculation of the CC cross section.[15]

To compare our one-parameter result with other experiments and with theory, we have computed $\sin^2\theta_W$ in two renormalization conventions. In the convention where $\sin^2\theta_W$ is defined in terms of the physical boson masses,[11] by the relation $\sin^2\theta_W = 1 - M_W^2/M_Z^2$,

TABLE II. Estimate of the systematic errors. The major sources of experimental and theoretical systematic errors are tabulated. The total systematic error was computed by adding all sources in quadrature. The systematic errors for the single-parameter $\sin^2\theta_W$ fit are enclosed in parentheses and the errors for $\sin^2\theta_W$ for the two-parameter fit are recorded in the second column. The two-parameter-fit errors are correlated.

	$\Delta\sin^2\theta_W/\sin^2\theta_W$		$\Delta\rho/\rho$
	Experimental sources		
NC/CC separation	(± 4.2%)	± 3.9%	± 1.3%
Muon elimination in CC hadron-energy determination	(± 2.0%)	± 5.4%	± 1.8%
Total experimental error	(± 4.7%	± 6.7%	± 2.2%
	Theoretical sources		
Strange sea magnitude $[xs(s) = (0.50 \pm 0.20)x\bar{u}(x)]$	(± 0.4%)	± 0.4%	± 0.1%
QCD corrections $(\Lambda = 200^{+200}_{-100}$ MeV/$c)^{a}$	(± 0.1%)	± 0.05%	± 0.05%
Slow rescaling $(M_c = 1.5 \pm 0.4$ GeV/$c^2)$	(± 2.0%)	± 1.8%	± 1.1%
Total theoretical error	(± 2.0%)	± 1.8%	± 1.1%
Total systematic error	(± 5.1%)	± 6.9%	± 2.5%

[a]Reference 6.

we found

$$\sin^2\theta_W = 0.247 \pm 0.012 \pm 0.013. \quad (4)$$

In the modified minimal-subtraction ($\overline{\text{MS}}$) scheme with the 't Hooft unit of mass chosen to be M_W,[11] which is appropriate for the SU(5) theories, we computed

$$\sin^2\theta_W = 0.245 \pm 0.012 \pm 0.013. \quad (5)$$

The errors quoted above are the statistical and systematic errors, respectively. These results are in agreement with previous measurements.[16]

Using only the neutrino data in our fit to reduce the sensitivity to the antiquark sea, we found $\sin^2\theta_W = 0.246 \pm 0.015$ (statistical error) with a χ^2/(degrees of freedom) of 2.5/2. Fitting all the neutrino and antineutrino data, but with the charmed-quark mass set equal to zero, we obtained a value of $\sin^2\theta_W = 0.228 \pm 0.012$ (statistical error), with a poor χ^2/(degrees of freedom) of 8.0/3. The value of $\sin^2\theta_W$ with no radiative correction ($\rho = 1$ and no muon-leg bremsstrahlung) was found to be 0.257 ± 0.012 (statistical error) with a χ^2/(degrees of freedom) of 3.1/3.

In summary, we have determined $\sin^2\theta_W$ and ρ from the integral ratios of NC events to CC events. Radiative corrections and slow rescaling corrections have been performed. The analysis employed strict kinematic and fiducial-volume cuts to reduce the backgrounds in the data. We found for the single-parameter fit, $\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013$.

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[14]The renormalization factors for $Q^2 = 20$ (GeV/c)^2 quoted in Ref. 11 were used to make our correction. The differences of these factors between $Q^2 = 11$ and 20 (GeV/c)^2 are negligible.

[15]If we hypothesize that the nucleon structure probed by the NC interaction could somehow be different from that probed by the CC interaction, a major constraint in the determination of $\sin^2\theta_W$ is lost. Nevertheless, with the NC structure functions and their experimental errors taken as given by Ref. 5, the error in $\sin^2\theta_W$ becomes enlarged to $\Delta\sin^2\theta_W/\sin^2\theta_W < \pm 15\%$ from this uncertainty.

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