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A PRECISE DETERMINATION OF THE ELECTROWEAK MIXING ANGLE
FROM SEMI-LEPTONIC NEUTRINO SCATTERING

The CHARM Collaboration

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Abstract

The cross-section ratio of neutral-current and charged-current semi-leptonic interactions of muon-neutrinos on isoscalar nuclei has been measured with the result: $R^\nu = 0.3093 \pm 0.0031$ for hadronic energy larger than 4 GeV. From this ratio we determined the electroweak mixing angle $\sin^2\theta_W = 0.236 + 0.012(m_c - 1.5) \pm 0.005$ (exp.) ± 0.003 (theor.), where m_c is the charm-quark mass in GeV/c^2 .

Following the discovery of the neutral weak-current [1] great efforts have been spent to test the prediction of the Glashow-Salam-Weinberg model that the coupling in all neutral-current phenomena depends on one single parameter, $\sin^2\theta_W$. This prediction is based on the Born approximation of the theory [2]. However, the theory being founded on gauge symmetries, radiative corrections are calculable to all orders and can be tested by experiments. The corrections to the Born terms are different for individual processes. Therefore, measurements of $\sin^2\theta_W$ made with sufficient precision and extracted from the data using the simple zero-order approximations should show characteristic differences for different reactions. It is this feature which provides a test of the gauge nature of the theory. A precise measurement of $\sin^2\theta_W$ in semileptonic neutrino scattering, combined with a direct measurement of the Z and W boson masses provides such a test [3].

We report on a high precision measurement of R^ν , the ratio of cross-sections of deep inelastic neutral-current (NC) and charged-current (CC) semileptonic interactions of neutrinos:

$$R^\nu = \sigma_{NC}^\nu / \sigma_{CC}^\nu, \quad (1)$$

which may be used to determine $\sin^2\theta_W$. For isoscalar targets it follows from isospin invariance alone that the contributions of u and d quarks to the NC and CC cross-sections are related to $\sin^2\theta_W$ by the equation [4]:

$$R^\nu = \sigma_{NC}^\nu / \sigma_{CC}^\nu = 1/2 - \sin^2\theta_W + 5/9 \sin^4\theta_W (1+r) \quad (2)$$

A measurement of the ratio of CC cross-sections for antineutrino and neutrino scattering, r , is needed to determine the small correction term, $5/9 \sin^4\theta_W \cdot r$.

The results reported here were obtained in a high statistics exposure of the CHARM neutrino detector in a 160 GeV/c narrow band beam (NBB), developed by Grant and Maugain [5] to provide a higher flux, resulting in an event sample that is a factor of 17 larger than that obtained during a previous exposure [6]. Neutrinos were produced in the decay of charge- and momentum-selected pions and kaons at the 450 GeV CERN Super Proton Synchrotron. The 120 m long beam line was tuned to a central momentum of 160 GeV/c and accepted particles with a momentum spread of $\pm 6\%$ (r.m.s.). About 8 m behind the last quadrupole, hadrons entered a 300 m long decay tunnel, which was evacuated to a pressure of 1 torr. At the end of the decay tunnel all surviving hadrons were absorbed in a 185 m long iron shield. Muons were ranged out by a combination of the iron shield and a 220 m long earth shielding following the iron.

The ejected proton intensity was measured using a beam current transformer and the beam position on the 3 cm diameter carbon target was carefully monitored. The detector was exposed to neutrino and antineutrino fluxes produced by 3.27×10^{18} and 0.90×10^{18} protons on target, respectively. Two beam current transformers placed just in front of the entrance of the decay tunnel, after the last quadrupole lens, measured the intensity of the secondary beam. The relative amounts of pions and kaons in the beam were determined experimentally using a helium filled differential Cerenkov counter. The measurements yielded the ratios $K^+/\pi^+ = 0.1282 \pm 0.0028$ and $K^-/\pi^- = 0.0630 \pm 0.0033$.

The CHARM neutrino detector is a fine-grain calorimeter followed by an iron spectrometer with a toroidal magnetic field, and surrounded by a magnetized iron frame. The calorimeter has a sampling step corresponding to one radiation length or 0.22 absorption length, with scintillators, pro-

portional drift tubes and streamer tubes as detecting elements. It is described in detail elsewhere [7]. The response of the calorimeter was recently calibrated in electron and pion beams in the range from 0.5 to 140 GeV/c [8]. The energy of hadron showers is measured by the scintillators with a resolution of $\sigma(E)/E = 0.487/\sqrt{(E/\text{GeV})} + 0.0127$. The lateral vertex position of hadron showers is determined by combining the measurements of all detection elements; it reaches a precision of better than 3 cm above 50 GeV. For this experiment the fiducial volume extended over 55 target plates leaving five plates at the beginning of the detector to reject incoming tracks and 18 plates at the end to ensure good shower containment. This resulted in a fiducial mass of 87 tons.

A special feature of the CHARM detector is the low detection threshold, which makes it possible to measure showers down to an energy of 2 GeV with a very high trigger efficiency. Care was taken to avoid problems caused by two interactions within the conversion time needed by the electronics of the detector elements. After each trigger the time between the trigger and the following interaction in the detector was recorded. Events followed by another interaction within 1.2 μsec , indicating the presence of a second interaction within the sensitive time of the proportional drift tubes, were rejected. This procedure induced an additional effective deadtime of $\sim 2\%$ which does, however, not affect the measurement of R^ν . The average total dead time was 17.1% in the neutrino exposure and 12.8% in the antineutrino one.

Interactions in the CHARM detector were classified by an automatic pattern-recognition program on an event-by-event basis. Selection criteria were applied which attempt to identify optimally the physical processes and to minimize the corrections needed to relate the visible cross-sections to the physical cross-sections.

Neutrino interactions are defined as events which have no entering charged tracks. A neutrino event is called a charged-current interaction if a muon is originating from the event vertex. A muon is assumed to originate from the event vertex if its extrapolated intercept with the vertex plane of the event lies within 30 cm of the measured shower vertex, or if sufficient energy is measured in a box around the extrapolated point. The muon has to be visible over a range corresponding to an energy-loss of at least 0.67 GeV. Its total range has to exceed 1 GeV energy-loss, corresponding to a penetration of 20 calorimeter planes. The visible range of a muon track is defined as the length, measured in equivalent range, between the first clearly visible point outside the shower and the last point on the track, as seen by the proportional tube system. Tube hits are deemed to be clearly visible points on a track if they are separated laterally by at least 5 quiet tubes from their neighbouring hits (15 cm isolation criterion). In addition they are required to be isolated from other hits, which do not belong to the muon track, in the longitudinal direction. These isolation criteria are much more strict than the ones used in a previous publication on the same subject [6] and tend to reject more tracks on the basis of the requirement of 0.67 GeV visible range.

All other neutrino event candidates were classified as neutral-current interactions. Only those events which have their vertex inside the fiducial volume and which have a shower energy of at least 2 GeV were analysed. Representations of a typical NC and CC event in the CHARM detector are shown in figure 1.

In order to obtain the final CC and NC event numbers from the automatic classification, a number of corrections have to be applied which will now be discussed. In table 1, these corrections to the data are summarized,

for hadron energies larger than 4 GeV. We have chosen this value to eliminate events which are not due to deep inelastic scattering, reducing contributions to R^ν by pseudo-elastic and coherent pion production in NC and CC interactions to the level of $\Delta R^\nu/R^\nu \leq 10^{-4}$.

Table 1: Neutrino event numbers ($E_h \geq 4$ GeV).

	Neutral current	Charged current
Uncorrected data sample	39239 ± 198	108472 ± 329
Trigger + filter efficiency	7 ± 4	0 ± 0
Scan correction	40 ± 40	60 ± 44
Cosmic and WB correction	-2310 ± 87	-4311 ± 119
Difference in energy cut	-	0 ± 129
Lost muons correction	-3737 ± 105	3735 ± 105
π and K decay	1892 ± 50	-1835 ± 50
Ke3 charged-current	-1768 ± 68	-106 ± 6
Ke3 neutral-current	-532 ± 20	-33 ± 2
Corrected event numbers	32831 ± 283	105982 ± 408

The trigger rate induced by cosmic-ray events is ≈ 4 kHz. A fast filter program reduced the cosmic ray induced background to the level of a few Hz, while retaining nearly all NC events. The combined trigger and filter ef-

efficiency of all NC events with a hadron energy above 4 GeV was found to be 99.98%.

The program recognized and flagged event topologies for which the automatic procedure could fail. These flagged events (~ 4000) were visually inspected in a double scan and corrected on a event-by-event basis. In addition to these flagged events a randomly selected sample totalling 5% of all triggers surviving the cosmic ray filter was scanned in order to determine the efficiency of the automatic pattern recognition program and to correct for it on a statistical basis. Out of ≈ 20000 events, 7 events were found to be misclassified, of which 3 CC and 2 NC events were wrongly assigned to be outside the fiducial volume. The results of this scanning allowed us to correct the errors introduced by the classification code to $\Delta R^V/R^V \leq 0.1\%$.

The corrections for wide-band (WB) and cosmic ray background are combined in table 1. The cosmic ray background contribution in the live time of the experiment was found to be $(1.42 \pm 0.02)\%$ for NC events and negligible for CC events. Events due to the so-called wide-band background, caused by neutrinos from hadrons of undetermined charge and momentum, decaying upstream of the decay tunnel were measured when the beam was blocked by a 1.5 m long Fe absorber. The procedure consists of defining the neutrino flux generated before the dump to be background, and the flux from decays downstream of the dump as "beam". A small correction for non-containment in the dump and for contributions of secondary particles created in the dump and in the residual gas of the decay tunnel was applied. The relative normalization of the periods when the dump blocked the entrance of the decay tunnel with respect to the standard running conditions was performed using the signal of the secondary hadron beam current transformer.

The uncertainty introduced by the subtraction of the cosmic and wide-band backgrounds amounts to $\Delta R^{\nu}/R^{\nu} \approx \pm 0.3\%$.

The energy deposition of the muon in the hadron shower region was subtracted from the hadron energy. The additional uncertainty in the hadron energy measurement introduced by this subtraction was taken into account as a source of systematic uncertainty for CC events.

CC events in which the primary muon cannot be identified are automatically classified as NC. Some of these lost CC events have muons with an energy less than 1 GeV. Another contribution to the loss of CC events is caused by muons of more than 1 GeV either leaving the sides of the detector before their energy loss is sufficiently large, or being obscured by the hadronic shower. A correction is required for these losses. The precision which can be reached in measuring R^{ν} depends in an essential way on the reliability of this correction. We therefore determined the correction by two independent methods. In one method the efficiency of recognizing primary muons is obtained by overlaying by computer simulated muons on real showers obtained by removing the original muon from CC events. In the other method the effective shower length distribution is calibrated by measuring the length of the hidden part of primary muon tracks in CC events, and using this distribution in a Monte-Carlo program to determine the muon recognition efficiency. The total correction induced by all sources of unidentified muons is 3.5% of the CC event rate. The two methods give consistent results to within 2% of the correction. In order to minimize systematic errors in the calculation of the correction a "reference-region" is defined relative to which the unseen muons are calculated. Charged-current events belong to the reference-region if the primary muon has a computed total energy in the range between 3 and 5 GeV. The ratio of all CC events with an

unseen muon and identified CC events in the reference region is calculated using the Monte-Carlo program described above. The absolute number of CC events where the muon was not recognized is obtained by multiplying this ratio with the actual number of CC events found in the reference region. Backgrounds in the reference region were taken into account. This procedure eliminates all errors introduced by uncertainties in the beam energy, the energy-loss of muons, the density of the detector and the slope of the y-distribution. This cancellation is exact for all such scale errors because the simulated events in the reference region scale with the number of events with lost muons. The systematic error is dominated by the determination of the shower length (± 0.5 calorimeter samplings) and is estimated to be $\pm 2.8\%$ of the correction, contributing an error of $\Delta R^\nu/R^\nu \approx \pm 0.4\%$.

A small fraction of NC events contains a track which fulfills the requirements of a primary muon of a CC event; these events are classified as CC events. This background is caused by decays of pions or kaons in the shower or by non-interacting hadrons, the so-called punch-through tracks. The correction is evaluated by analysing CC events in which the primary muon has been removed. The fraction of these events where another track is found which satisfies the muon recognition criteria yields the correction. This procedure is done in bins of the hadron energy in order to correct for the difference of CC and NC hadron energy distributions. A small contribution, present in CC but not in NC events is due to prompt muons from charm decays and can be subtracted with sufficient precision. The size of this correction, integrated for hadron energy above 4 GeV, is $\approx 4.8\%$ of the NC rate, determined with a fractional error of $\pm 2.6\%$, contributing an error of $\Delta R^\nu/R^\nu \approx \pm 0.2\%$.

Both NC and CC interactions of electron-neutrinos originating from K_{e3} -decays in the beam are classified as NC events. The contribution of these events amounts to $\sim 7\%$ of the muon-neutrino induced NC events. A small correction was applied for events with hadron showers generating a decay muon which fulfills the requirements of a primary muon, causing these events to be classified as CC events. Measurement of the K/π ratio with an accuracy of $\sim \pm 3\%$, determines the $Ke3$ correction with a fractional error of $\pm 4\%$, corresponding to $\Delta R^\nu/R^\nu \approx \pm 0.3\%$.

Taking these corrections into account we obtained for events with hadronic energy greater than 4 GeV: $R^\nu = 0.3098 \pm 0.0031$ for the calorimeter material and, correcting for the small deviation from isoscalarity:

$$R^\nu = 0.3093 \pm 0.0031 \quad (3)$$

For the ratio of the total antineutrino and neutrino charged-current cross-sections we obtained: $r = 0.439 \pm 0.011$. Correcting for the different spectra in neutrino and antineutrino exposures gives:

$$r = 0.456 \pm 0.012 \quad (4)$$

The uncertainty on r is dominated by the event-statistics (1.4%), WB background subtraction (0.8%) and the relative normalization error of the $\bar{\nu}$ to ν flux (2.0%).

Using equation (2) and neglecting all corrections to this equation due to the presence of other than only u and d quarks, a raw value of $\sin^2\theta_W$, assuming $\rho = 1$, is obtained:

$$\sin^2\theta_W|_{\text{raw}} = 0.2356 \pm 0.0050 \quad (5)$$

The result (5), deduced in the approximations of equation (2), has to be corrected for various effects in a quark-parton model (QPM) framework. The different components of the corrections applied to obtain $\sin^2\theta_W$ from R^ν and r measured with a 4 GeV hadron energy cut are given in table 2 and will now be discussed.

Table 2: Corrections to $\sin^2\theta_W$ ($E_h \geq 4$ GeV).

Source	$\Delta\sin^2\theta_W$	theor. uncertainty
muon mass	+ 0.0011	± 0.0001
W^2 thresholds, F_L	+ 0.0005	± 0.0005
K.M. mixing matrix		± 0.0010
Strange sea at $m_c=0$	- 0.0074	± 0.0010
Charm sea at $m_c=0$	+ 0.0015	± 0.0010
Radiative corrections	- 0.0092	± 0.0020
Total uncertainty (fixed m_c)		± 0.0030
Charm mass ($m_c = 1.5$ GeV/ c^2)	+ 0.0140	
Total ($m_c = 1.5$ GeV/ c^2)	+ 0.0005	± 0.0030

The muon mass causes a small phase space suppression in CC events and the final state invariant mass threshold depends on the produced quark fla-

voir. A small correction for the longitudinal structure function (F_L) has been applied; the F_L distribution was taken from a measurement done by this collaboration [9]. The strange quark sea and the charm quark sea in the nucleons have been taken into account. In addition, charged current interactions changing a light quark into a charm-quark are kinematically suppressed because of the mass of the charm-quark, m_c . A fixed mass, $m_c = 1.5$ GeV/c², was chosen, and the threshold effects were computed using the slow rescaling procedure [10]. The distributions were determined from dimuon production data in deep inelastic neutrino and muon scattering, respectively [11] [12]. In these calculations, we used Kobayashi-Maskawa (K.M.) mixing matrix elements obtained [13] assuming three families of quarks and requiring unitarity of the matrix.

The preceding corrections change the electro-weak mixing angle by $\Delta \sin^2 \theta_W = + 0.0097$.

The major theoretical uncertainties of these corrections are due to the limited knowledge of the momentum-weighted contents of s and c quarks in the nucleon, the K.M. mixing elements and threshold-effects in charm-production [4]. These uncertainties are summarized¹ in table 2. The largest uncertainty is in the choice of the charm-quark mass m_c which affects the threshold suppression of charm-production. We, therefore, present the result on $\sin^2 \theta_W$ as a function of m_c with $m_c = 1.5$ GeV/c² as the central value. This linear approximation is valid in a range: $1 \text{ GeV/c}^2 \leq m_c \leq 2 \text{ GeV/c}^2$.

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¹ The uncertainty on the strange sea is estimated taking into account m_c threshold suppression.

The effect of QED and electroweak radiative corrections on $\sin^2\theta_W$ was estimated following Bardin et al. [14], in the on-shell renormalization scheme [15]. The calculation was performed using a set of computer programs made available to us by D.Yu. Bardin. Setting the top and Higgs masses to 45 GeV and 100 GeV, respectively, we found: $\Delta\sin^2\theta_W = -0.0092$, and estimated a precision of ± 0.002 for this computation.

The total theoretical uncertainty in the determination of $\sin^2\theta_W$, excluding the uncertainty on m_c , is estimated to be of the order of ± 0.003 . Higher twist effects are supposed to be small and were neglected. For simplicity, we assumed the slow rescaling procedure to be valid. We do not quote additional systematic errors for these assumptions.

Applying both quark-parton model and radiative corrections, we obtain the final result:

$$\sin^2\theta_W = 0.236 + 0.012(m_c - 1.5) \pm 0.005 \text{ (exp.)} \pm 0.003 \text{ (theor.)} \quad (6)$$

where m_c is the charm-quark mass in GeV/c².

The analysis was repeated for hadron energies larger than 9, 16 and 25 GeV, and the resulting values of R^v are shown in figure 2a together with the quark-parton model prediction which is normalized to the data at 4 GeV. We note good agreement confirming the validity of the model used to correct the data. Figure 2b shows the values of $\sin^2\theta_W$ after quark-parton model and radiative corrections for the same hadron energy cuts. We note that the value of $\sin^2\theta_W$ does not vary with the hadron energy cut, thus demonstrating the consistency of the methods used.

This result can be compared with those obtained in other semi-leptonic neutrino scattering experiments. Starting from a previous measurement

(1979) of R^V and r by this collaboration [6] and applying the same quark-parton model and radiative corrections, we obtained: $\sin^2\theta_W = 0.223 \pm 0.014$ (exp.). The CDHS group obtained recently [16]: $\sin^2\theta_W = 0.225 \pm 0.013(m_c - 1.5) \pm 0.005$ (exp.) ± 0.003 (theor.). Both results are in good agreement with the new value we report. The most recent results from proton-antiproton collisions derived from measurements of M_W and M_Z and applying radiative corrections are [17]: $\sin^2\theta_W = 0.214 \pm 0.006$ (stat.) ± 0.015 (syst.) from the UA1 collaboration and $\sin^2\theta_W = 0.232 \pm 0.004$ (stat.) ± 0.008 (syst.) from the UA2 collaboration. These results are in very good agreement with the value we obtain from semi-leptonic neutrino scattering. The systematic error reflects the scale uncertainty of the calorimeter calibration in the measurement of M_W and M_Z . Future, high statistics experiments will allow to eliminate this uncertainty by deriving $\sin^2\theta_W$ from the ratio of W and Z masses.

Without electroweak radiative corrections, the values derived from the W mass, $\sin^2\theta_W = 0.216 \pm 0.004 \pm 0.008$ (syst.) (UA2), and from semi-leptonic neutrino scattering, $\sin^2\theta_W = 0.245 \pm 0.005$, differ appreciably, by two to three standard deviations. Thus, experiments seem to indicate that these corrections are required.

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Figure 1: Neutral-current (a) and Charged-current (b) events recorded in the CHARM detector.

Figure 2: Dependence of R^v (a) and $\sin^2 \theta_W$ (b) on the hadron energy (E_h) cut.