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

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CHARM Collaboration

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Abstract

The neutral-current and charged-current cross-section ratio of semi-leptonic interactions of muon-neutrinos on isoscalar nuclei (marble) has been measured with the result: $R_\nu = 0.3098 \pm 0.0031$ for hadronic energy larger than 4 GeV. From this ratio we determined the electroweak mixing angle $\sin^2\theta_W = 0.236 \pm 0.005$ (exp.) ± 0.005 (theor.)

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1. Introduction

After the discovery of the weak neutral-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, $\sin^2\theta_W$. Indeed, a unique value of this parameter can explain the couplings measured in many different processes, including leptonic and semileptonic neutrino scattering, asymmetries in electron-nucleon, electron-positron and muon-nucleon interactions, parity violating effects in atomic transitions, and the masses of the W and Z bosons [2].

This prediction is based on the Born approximation of the theory [3]. In the corrections to the Born terms different processes pick up different correction terms. Measurements of $\sin^2\theta_W$ made with sufficient precision and extracted from the data using the simple zero-order approximations should show differences for different reactions. The differences can be calculated and a comparison with experiments provides therefore a test of the gauge nature of the theory. The present experiment reaches a precision of $\Delta\sin^2\theta_W = \pm 0.005$ in neutrino scattering, matched in sensitivity to future measurements of the W and Z masses at the CERN $p\bar{p}$ collider [4].

2. Experimental Method

We have used a measurement of R_ν, the ratio of cross-sections of deep inelastic neutral-current (NC) and charged-current (CC) semileptonic interactions in a neutrino beam

$$R_\nu = \sigma_{NC}{}^\nu/\sigma_{CC}{}^\nu \tag{1}$$

to obtain a value of $\sin^2\theta_W$. It has been shown [5] that 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:

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

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

We report here results of an experiment using data taken in 1984 to measure R^ν with high precision [6]. An upgraded version of the narrow-band beam was used at a central momentum of 160 GeV/c with nearly a factor two higher flux than previously. The analysis will be described in some detail in the following paragraphs. Emphasis is given on the corrections we applied to extract the physical ratio R^ν from the visible one.

2.1 The Experimental Set-up

Data were taken in the 160 GeV/c narrow band beam (NBB), developed by Grant and Maugain [7] as a high flux version of the CERN NBB optics. It satisfies the conditions for a precision measurement of R^ν [8], namely:

- A sufficiently high average neutrino energy, needed for efficient pattern recognition in the CHARM detector.
- Low background contributions, measurable with high accuracy.
- The possibility to measure the relative $\bar{\nu}/\nu$ flux normalization accurately.
- A calculable neutrino energy spectrum.
- High event rate.

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, proportional drift tubes and streamer tubes as detecting elements. It is described in detail elsewhere [9]. The fiducial mass in this experiment was 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 as low as 2 GeV. The overall trigger efficiency for NC showers with an energy above 2 GeV has been determined to be 99.93%.

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 a TDC recorded the time between the trigger and the following interaction in the detector. Events followed by another interaction within 1.2 μsec, indicating the presence of the second interaction in the gate of the proportional drift tubes, were rejected. This procedure induced an additional effective deadtime of ~ 2% which does not affect the measurement of R^{ν}.

2.2 Event Classification and Corrections

Interactions in the CHARM detector are classified by an automatic pattern-recognition program on an event-by-event basis. Selection criteria are 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 it contains a muon originating from the event vertex. The muon has to be visible (outside the hadronic shower) over a range corresponding to an energy-loss of at least 0.67 GeV. Its total range has to exceed 1 GeV energy-loss. All other neutrino-event candidates are 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 are analysed. 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.

The classification efficiency of the automatic pattern recognition is very high. The program recognized and flagged event topologies for which the automatic procedure could fail. A visual inspection of these flagged events (~ 4000) together with a double scan of 20000 randomly selected events allowed us to correct the errors introduced by the classification code to $\Delta R^{\nu}/R^{\nu} \leq 0.1\%$.

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 simulated muons over 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 within 2% of the correction value. The systematic error is dominated by the determination of the shower length ($\pm$ 0.5 calorimeter samplings) and is estimated to be $\pm$ 2.8% of the correction, contributing an error of $\Delta R^{\nu}/R^{\nu} \simeq \pm 0.4\%$.

A small fraction of NC events contains a track which fulfils 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 calculated by studying the fraction of CC events in which after removing the primary muon another track is found which satisfies the muon recognition criteria. 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. This procedure is done in bins of the shower energy in order to correct for the different CC and NC shower energy distributions. The size of this correction, integrated for shower energy above 2 GeV, is $\simeq$ 5.5% of the NC rate, determined with a fractional error of $\pm$ 2.6%, giving a contribution of $\Delta R^{\nu}/R^{\nu} \simeq \pm 0.2\%$.

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 ~ 7% of the muon-neutrino induced NC candidates. Measurement of the K/π ratio with an accuracy of ~ $\pm$ 3%, determines this correction with a fractional error of $\pm$ 4%, corresponding to $\Delta R^{\nu}/R^{\nu} \simeq \pm 0.3\%$.

Events induced by the neutrino flux from decays of pions and kaons before the decay tunnel were measured when the entrance of the decay tunnel was blocked by an absorber and subtracted. The uncertainty introduced by this so-called wide-band (WB) background amounts to $\Delta R^{\nu}/R^{\nu} \simeq \pm 0.3\%$ in the neutrino exposure.

The trigger rate induced by cosmic-ray events is $\simeq$ 4 kHz. A fast filter program reduced the cosmic ray induced background to the level of a few Hz, while retaining 99.96% of all NC events with a shower energy above 2 GeV. The remaining background contribution in the live time of the experiment was found to be $\simeq$ (1.42 $\pm$ 0.02)% for NC events (negligible for CC events) and was subtracted.

In Table 1, these corrections to the data are summarized, for shower energy above 4 GeV. The same analysis was repeated with shower energy cut at 2, 4, 9, 16 and 25 GeV; since the corrected value of $\sin^2\theta_W$ we obtain is independent of this cut, we quote in the following the results with a 4 GeV cut, which minimizes our uncertainties.

Taking these corrections into account we obtain for events with hadronic energy greater than 4 GeV:

$$R^{\nu} = 0.3098 \pm 0.0031$$

For the ratio of the total antineutrino and neutrino charged-current cross-sections we obtain:

$$r = 0.439 \pm 0.011$$

The uncertainty on r is dominated by the event-statistics (1.4%), WB background subtraction (0.8%) and relative normalisation 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, the raw value of $\sin^2\theta_W$ is obtained:

$$\sin^2\theta_W = 0.235 \pm 0.005 \qquad \text{(assuming } \rho = 1\text{)}$$

2.2.1 Quark-Parton Model Corrections.

The "raw" value, deduced in the approximations of equation (2), must be corrected for the following effects, in a quark-parton model framework:

- A correction was made for the final state invariant mass threshold depending on the produced quark flavour.

Table 1: Corrections to the Data (ν exposure, E_h > 4 GeV)

	NC	CC	$\Delta R^\nu/R^\nu$
Raw event numbers	39239 ± 198	108472 ± 329	0.6%
Corrections Applied and Errors in R^ν:			
Trigger and filter efficiency	7.3 ± 3.8	0.0 ± 0.0	
Scan correction	40 ± 39	60 ± 44	
WB background	-1998 ± 87	-4308 ± 119	
Cosmic background	-312 ± 8	-3.1 ± 0.8	≃ 0.5%
Clean data sample	36976 ± 225	104220 ±361	
Difference in energy cut	–	0 ± 129	0.1%
Muon recognition losses	-3738 ± 105	3735 ± 105	0.4%
π/K decays in the shower	1892 ± 50	-1835 ± 50	0.2%
K_{e3} decays	-2300 ± 88	-139 ± 8	0.3%
Corrected event numbers	32831 ± 283	105982 ± 408	
Total systematic error			0.8%
Total error			1.0%

- The strange quark sea and the charm quark sea in the nucleons were taken into account: their distributions were determined from dimuon production data in deep inelastic neutrino and muon scattering respectively.
- Charged current interactions changing a light quark into a charm-quark are kinematically suppressed by the mass of the charm-quark, m_c. A fixed mass, m_c = 1.5 GeV, was chosen, and the threshold effects were computed using the slow rescaling procedure [10].

In these calculations, we used Kobayashi-Maskawa mixing matrix elements obtained [11] assuming three families of quarks and requiring unitarity of the matrix. These corrections gave the following net effect on the electro-weak mixing angle: $\Delta\sin^2\theta_W = +\ 0.010$.

The theoretical error is dominated by the uncertainty in the c−quark mass to be used to calculate threshold effects; using m_c = (1.5 ± 0.3) GeV we find $\Delta\sin^2\theta(m_c) = \pm\ 0.004$. Other contributions to the theoretical error are introduced by uncertainties in the momentum-weighted content of s and c quarks in the nucleon, and the elements the Kobayashi-Maskawa (K.M.) mixing matrix.

With the present experimental knowledge of the c and s quarks content in the nucleon, of the c-quark mass, and of the K.M. matrix elements with the unitarity conditions mentioned above, we estimate a theoretical uncertainty in the determination of $\sin^2\theta_W$ of ≅ ± 0.005. An additional uncertainty due to higher twist terms is estimated to be smaller than 0.005 [5]. These uncertainties are inherent in the hadronic nature of the target and do not occur in purely leptonic processes such as neutrino-electron scattering [12].

2.2.2 Radiative Corrections

The effect of QED and electroweak radiative corrections on $\sin^2\theta_W$ was calculated following Bardin et al. [13], in the on-shell renormalization scheme of Sirlin and Marciano [14]. With the definition $\sin^2\theta_W = 1 - M^2_W/M^2_Z$, we find: $\Delta\sin^2\theta_W = -0.009$.

We estimate a precision of ± 0.002 for this computation. Applying both quark-parton model and radiative corrections, we obtain the result:

$$\sin^2\theta_W = 0.236 \pm 0.005 \text{ (experimental error)}$$

Our result can be compared with the most recent results from the UA1 and UA2 collaboration derived from measurements of M_W and M_Z, giving [15:.] $\sin^2\theta_W = 0.214 \pm 0.006$ (stat.) $\pm$ 0.015 (syst.) from UA1 and $\sin^2\theta_W = 0.232 \pm 0.004$ (stat.) $\pm$ 0.008 (syst.) from UA2.

3. Conclusion

The CHARM-collaboration has performed an experiment aiming at a precision determination of $\sin^2\theta_W$ using semi-leptonic neutrino scattering. The analysis shows consistency with previously published results obtained with the same detector [16]. An experimental precision of $\Delta\sin^2\theta_W \cong 0.005$ has been obtained. The experiment therefore matches the precision of future direct measurements of the $W^{\pm}$ and Z^0 masses at the upgraded CERN Sp$\bar{p}$S collider and at LEP.

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