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Neutral current coupling constants from neutrino- and antineutrino-electron scattering

CHARM II Collaboration

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We are reporting on a determination of neutral current coupling constants from a study of differential cross sections of muon-(anti)neutrino-electron scattering. The results were obtained with the CHARM-II detector which was exposed to the CERN wide band neutrino beam in the years 1987-1990. A total of about 2100 νe and 2200 $\bar{\nu}$e scattering events were observed. From a comparison between the data and predicted event distributions, the effective vector and axial-vector neutral current coupling constants of the electron were determined to be $g_V^e = -0.025 \pm 0.019$ and $g_A^e = -0.503 \pm 0.018$.

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1. Introduction

Very precise measurements of electroweak parameters have been made at the electron–positron collider LEP at CERN [1]. In view of higher order corrections, however, it remains of great interest to compare these measurements at the Z^0-resonance with those performed at lower energy where processes occur by virtual Z^0 exchange. Neutrino–electron scattering is perfectly suited for such a comparison, since the process is purely leptonic and, in terms of coupling constants, nearly equivalent to the annihilation of electrons and positrons into lepton pairs. In a previous publication [2], we obtained a result for the electroweak mixing angle, $\sin^2\theta_w$, derived from a measurement of the cross section ratio $R=\sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$. We present here a new, improved analysis based on a measurement of the differential cross sections of muon-neutrino and muon-antineutrino scattering off electrons [3]

$$\frac{d\sigma_{\bar{\nu}}^{\nu}}{dy}=\frac{G_F^2 m_e}{2\pi}E_\nu \times[(g_V \pm g_A)^2+(g_V \mp g_A)^2(1-y)^2]\,, \qquad (1)$$

where $y=\frac{1}{2}(1-\cos\theta^*)$ and θ^* is the scattering angle in the CM system, g_V and g_A the vector and axial-vector coupling constants of the electron to the neutral current respectively. In addition we include the knowledge on absolute ν-fluxes and selection efficiencies. This new method enables us to determine simultaneously two electroweak parameters and increases the experimental sensitivity because of the use of energy distributions of the events.

The CHARM II detector was built to study neutrino–electron scattering [4]. It consists of a massive target calorimeter followed by a muon spectrometer. The calorimeter is instrumented with streamer tubes equipped with digital and analog readout to measure the energy and the direction of particles produced. The detector was exposed to the horn focused wide band neutrino beam (WBB) at CERN. Neutrinos were produced by a 450 GeV proton beam accelerated in the super proton synchrotron (SPS).

The signature of neutrino–electron scattering is a single, forward scattered electron producing an electromagnetic shower in the calorimeter. The variable $E_e\theta_e^2$, the product of electron energy and the square of the scattering angle, is kinematically constrained to values smaller than 1 MeV. This fact is used to separate νe-scattering from the background of semileptonic events which has a broad distribution.

2. Analysis method

The differential cross section as it is given in eq. (1) is valid only for muon-(anti)neutrinos. Due to the contamination of neutrinos of opposite helicity and electron-neutrinos (ν_e and $\bar{\nu}_e$) in the neutrino beam, the measured differential cross sections contain contributions from four different neutrino–electron scattering processes. Since the four differential cross sections depend on the same electroweak parameters, the measurements in the ν- and $\bar{\nu}$-beam [#1] lead to a simultaneous measurement of two electroweak parameters as will be shown below.

The general form of the neutrino–electron scattering cross section can be written as

$$\frac{d\sigma}{dy}=\frac{G_F^2 m_e}{2\pi}E_\nu\sum_{i=1}^{3}A_i g_i\,, \qquad (2)$$

where the g_i are different combinations of electroweak coupling constants:

$$g_1=(g_V+g_A)^2\,,$$
$$g_2=(g_V-g_A)^2\,,$$
$$g_3=(2+g_V+g_A)^2\,. \qquad (3)$$

The expressions A_i are given in table 1 for the four processes involved. The third term in (2) accounts for the interference of neutral and charged currents in electron-neutrino–electron scattering.

The four differential cross sections (2) depend on two parameters only, either on g_A and g_V, or using the standard model relation between the coupling constants and the electroweak mixing angle:

$$g_V^e=\rho(-\tfrac{1}{2}+2\sin^2\theta_w) \quad\text{and}\quad g_A^e=-\tfrac{1}{2}\rho\,, \qquad (4)$$

on $\sin^2\theta_w$ and ρ, the relative coupling strength of the neutral current with respect to the charged current.

[#1] We call the beam produced by focusing positive parents the ν-beam and by negative parents the $\bar{\nu}$-beam.

Table 1
Terms of the differential cross section for different processes.

Process	A_1	A_2	A_3
$\nu_\mu e \to \nu_\mu e$	1	$(1-y)^2$	0
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	$(1-y)^2$	1	0
$\nu_e e \to \nu_e e$	0	$(1-y)^2$	1
$\bar{\nu}_e e \to \bar{\nu}_e e$	0	1	$(1-y)^2$

The measured event rate, e.g., in the neutrino beam is given by

$$\frac{\mathrm{d}n^{\nu e}}{\mathrm{d}y} = \sum_{i=1}^{3} f_i^{\nu e} g_i \,, \tag{5}$$

where the differential distributions $f_i^{\nu e}$ contain all information about the target density, the neutrino flux and energy spectra, the cross section expressions A_i, and the experimental resolutions and acceptances. All these quantities are either known by calculation or measured as described below.

Electroweak parameters are obtained from a simultaneous fit of modelled differential distributions $f_i^{\nu e}$ to the data collected in the ν- and $\bar{\nu}$-beam. In this way a direct determination of the coupling constants is possible. Previous νe experiments have also deduced the coupling constants from ν_μe and $\bar{\nu}_\mu$e cross sections [5,6] but with much lower statistics.

3. Data analysis

The data presented here were collected during the years 1987–1990 and represent ≈80% of the final statistics. In total 2.1×10^{19} protons were delivered to the target. The data-taking in neutrino and antineutrino mode was alternated every 2–3 days to equalize the detection efficiency and protons were shared in such a way that the number of neutrino–electron and antineutrino–electron scattering candidates was nearly equal.

3.1. Neutrino flux and energy spectra

The neutrino flux was obtained from a monitor reaction with known cross section, namely inclusive neutrino–nucleon scattering. The analysis of these reactions was based on two different methods.

For the first method neutrino-induced events were selected without separation into charged current (CC) and neutral current (NC) with an energy threshold of 3 GeV (so-called minimum bias events). Based on the known CC cross section and NC/CC cross section ratio the number of these events was converted into an integrated neutrino flux. The second method is based on CC interactions in a restricted fiducial volume in the neutrino energy range 15–60 GeV where the CC cross section is well known. Good agreement of observed and simulated differential distributions ensured that acceptance corrections were correctly calculated. The neutrino flux was then scaled to the full energy range.

The results of the two methods show good agreement. The acceptance corrections and uncertainties in the beam composition are different for the two samples. Thus the systematic error was reduced. The absolute flux in the $\bar{\nu}$-beam was not determined in the same way, since the CC cross section is not so well known for $\bar{\nu}_\mu$. Instead it was determined from a measurement of the flux ratio $f = \Phi_{\bar{\nu}}/\Phi_\nu$ in the neutrino and antineutrino beam which had already been evaluated for the measurement of the ratio of ν_μe and $\bar{\nu}_\mu$e cross sections [2].

A total energy weighted flux of main component neutrinos in the fiducial volume of the detector of $(1.68\pm0.08)\times10^{18}$ GeV and $(1.68\pm0.09)\times10^{18}$ GeV was obtained for the ν- and $\bar{\nu}$-beam, respectively. The total uncertainty on the flux measurement was found to be 4.7% and 5.2% for the neutrino and antineutrino beam, respectively.

For the flux normalization as well as for the modelling of the νe event distributions the knowledge of the neutrino beam properties is essential. The neutrino beam spectra and the relative flux of opposite helicity components were obtained from a new analysis of charged current events with low momentum transfer. Acceptance and resolution effects were unfolded. The electron-neutrino components were determined by Monte Carlo methods. The results on the beam composition are summarized in table 2.

3.2. Neutrino–electron scattering event selection

The selection of neutrino–electron scattering candidates was described previously [2]. The selection

Table 2
Neutrino beam composition.

Beam	Component	Relative abundance	$\langle E_\nu \rangle$ (GeV)
ν	ν_μ	1	23.7 ± 0.3
	$\bar{\nu}_\mu$	0.072 ± 0.004	19.2 ± 0.5
	ν_e	0.0087 ± 0.0013	44.0 ± 2.2
	$\bar{\nu}_e$	0.0017 ± 0.0003	33.8 ± 1.7
$\bar{\nu}$	ν_μ	0.136 ± 0.007	26.3 ± 0.5
	$\bar{\nu}_\mu$	1	19.1 ± 0.2
	ν_e	0.0071 ± 0.0011	36.5 ± 1.8
	$\bar{\nu}_e$	0.0043 ± 0.0006	37.0 ± 1.9

efficiencies which have to be known for this analysis were determined using test beam data and found to be independent of the shower energy. A careful check of possible systematic effects due to detector instabilities was performed. The overall uncertainty of the selection efficiency of neutrino–electron scattering candidates was found to be $\pm3.4\%$.

The resolution functions for the energy and direction determination were obtained from a calibration of the detector in a test beam [7]. We determined the energy of electromagnetic showers from the number of streamer tube hits in the event. The relative resolution was found to be

$$\frac{\Delta E_e}{E_e}=\frac{0.09}{\sqrt{E_e/\mathrm{GeV}}}+0.11\,. \tag{6}$$

The absolute energy scale uncertainty is estimated to be 5%. For the angular resolution,

$$\Delta\theta_e^{\mathrm{proj}}=\left(\frac{27(E_e/\mathrm{GeV})^{-2}+14}{\sqrt{E_e/\mathrm{GeV}}}+1\right)\mathrm{mrad} \tag{7}$$

was found [#2].

3.3. Background determination

The background consists of semileptonic neutrino reactions producing predominantly electromagnetic final states. In total four processes are expected to contribute to the background. The main contribution is coming from coherent (π^0 coh.) an diffractive (π^0 diff.) neutrino production of single neutral pions in NC interactions. Electromagnetic showers are also produced in quasi-elastic neutrino–nucleon reactions of electron-neutrinos (ν_e q.e.). A small fraction of the background is due to inclusive neutrino reactions (incl.) with a large electromagnetic component in the final state. The background distributions f_i^{BG} are modelled using data and Monte-Carlo techniques as described in ref. [2].

4. Results

4.1. The fit procedure

The experimental data and the theoretical predictions are described as double differential distributions in the kinematic variables E_e and $E_e\theta_e^2$.

$$f=\frac{\mathrm{d}^2n}{\mathrm{d}E_e\,\mathrm{d}(E_e\theta_e^2)}\,. \tag{8}$$

They discriminate between signal and background in the variable $E_e\theta_e^2$, and determine the background composition because of their different energy (E_e) distributions (see fig. 1).

The task of the final analysis step is to fit the predicted distributions p of the neutrino–electron scattering signal and the background processes,

$$p=\sum_{i=1}^{3} f_i^{\nu e}g_i+\sum_{i=1}^{4} f_i^{\mathrm{BG}}b_i\,, \tag{9}$$

to the experimental distributions $d=f^{\,\mathrm{data}}$. The coefficients b_i determine the contributions of the four background processes.

The theoretical prediction for neutrino–electron scattering was corrected for higher order QED effects [8]. The coupling constants determined from this fit are therefore effective values including, but not corrected for, higher order electroweak effects.

The fit was performed using distributions with non-equidistant binning according to the experimental resolutions. The energy range from 3 to 24 GeV was subdivided in 22 bins, and the $E\theta^2$ range from 0 to 72 MeV in 16 bins, leading to 352 bins in the two-dimensional distributions. The fit was performed to both neutrino and antineutrino data simultaneously, hence to 704 bins.

[#2] This is equivalent to $\Delta\theta_e^{\mathrm{proj}}\approx 17\ \mathrm{mrad}/\sqrt{E_e/\mathrm{GeV}}$ in the energy range of our analysis.

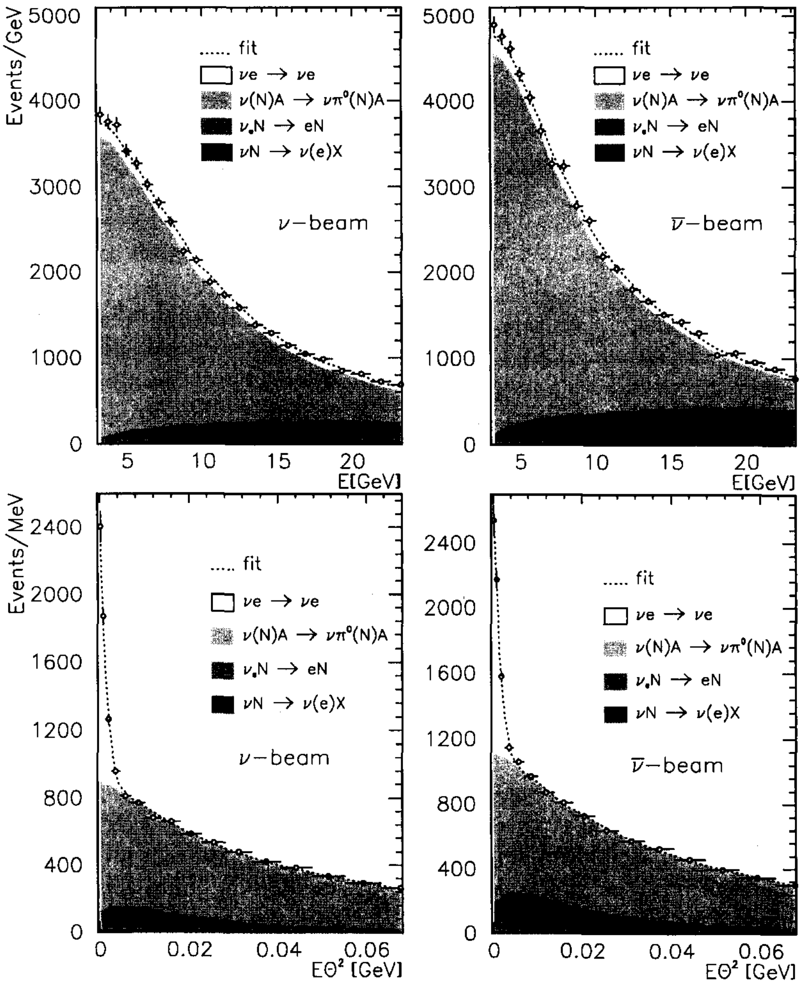

Fig. 1. Experimental data and the result of the best fit: data are shown as circles and the fit results are displayed as a dashed line. Only the projections in E_e and $E_e\theta_e^2$ of the two-dimensional distributions are shown. The different background components are added on top of each other.

The coupling constants g_V and g_A and the background composition b_i were taken as free parameters. With the ratio of diffractive to coherent pion production (b_2/b_1) constrained to be equal in neutrino and antineutrino beam data [9] this adds up to nine free parameters. The result of the best fit ($\chi^2=703$ for 695 DOF) is illustrated in fig. 1 and summarized in table 3. From the fit results the number of νe scattering events can be extracted. A total of

2105 ± 69 and 2215 ± 76

events are present in the ν and $\bar{\nu}$ data sample, respectively.

The fourfold ambiguity in the determination of g_V and g_A which is expected from the quadratic dependence of the cross sections on the couplings, is reduced to a twofold one owing to the presence of ν_e and $\bar{\nu}_e$ components in the beam. About 10% of the νe events are induced by electron-neutrinos, which select two solutions. Results from $e^+e^-\to e^+e^-$ experiments [10] resolve the remaining ambiguity.

The systematic errors are dominated by uncertain-

Table 3
Results of the fit to neutrino and antineutrino data. The errors are statistical. The coefficients b_i are the number of background events in the full fit range.

	Fit parameter					
	g_V	g_A	b_1 (π^0 coh.)	b_2/b_1	b_3 (ν_e q.e.)	b_4 (incl.)
ν-beam	-0.0254 ± 0.0138	-0.5027 ± 0.0069	22238 ± 1335	0.34 ± 0.06	4234 ± 233	681^{+194}_{-358}
$\bar{\nu}$-beam	-0.0254 ± 0.0138	-0.5027 ± 0.0069	25723 ± 1542	0.34 ± 0.06	7413 ± 269	381^{+224}_{-380}

Table 4
Systematic errors.

Error source	δg_V	δg_A
neutrino flux	0.006	0.009
selection efficiency	0.002	0.009
experimental resolutions	0.001	0.001
energy scale	0.002	0.004
background	0.011	0.009
beam spectra and composition	0.005	0.002
systematic error	0.014	0.016
statistical error	0.014	0.007
total	0.019	0.018

ties of the background determination, of the neutrino flux measurement and of the selection efficiency. A break down of the error sources which contribute to the uncertainties in the determination of the electroweak couplings is shown in table 4.

4.2. Discussion

The results for the effective vector and axial-vector coupling constants from neutrino–electron scattering are

$$g_V^e(\nu e) = -0.025\pm0.019\,,$$

$$g_A^e(\nu e) = -0.503\pm0.018\,,$$

where the statistical and systematic errors have been combined in quadrature.

This result can be compared with the measurements at LEP. The Z^0 exchange diagram for νe-scattering is related by crossing symmetry to the annihilation process $e^+e^-\to e^+e^-$ via Z^0 exchange. However, the two measurements refer to different Q^2 scales. Differences of the two couplings at the two scales ($Q^2=0.01$ GeV^2 and $Q^2=m_Z^2$) are expected to arise from the running of the fine structure constant α and the effect of the neutrino charge radius. However, these different contributions cancel almost completely, resulting in a difference of $g_V^e(\nu e) - g_V^e(\mathrm{LEP}) = -0.002$ while individual contributions are larger by an order of magnitude [#3].

Thus it is possible to compare our result directly with those obtained from a measurement of the partial width Γ_{ee} at the Z^0 resonance and the forward–backward asymmetry A^{FB} at LEP. Fig. 2 shows that results from neutrino–electron scattering have reached comparable precision in g_V^e. The agreement of the measurement performed at $Q^2\approx0.01$ GeV^2 with those performed at $Q^2=m_Z^2$ is remarkable.

Using the parametrization (4) for the coefficients g_i in (2) it is also possible to perform a fit to the data using the electroweak mixing angle $\sin^2\theta_w$ and the relative coupling strength ρ of neutral and charged currents as free parameters:

$$\sin^2\theta_{\nu e} = 0.237\pm0.007_{\mathrm{stat}}\pm0.007_{\mathrm{syst}}\,,$$

$$\rho_{\nu e} = 1.006\pm0.014_{\mathrm{stat}}\pm0.033_{\mathrm{syst}}\,.$$

Using the $\overline{\mathrm{MS}}$ renormalization scheme [13] we can correct our result for higher order electroweak effects. This renormalization scheme is advantageous, because the dependence of this correction on unknown quantities, like m_t and m_H, is rather small. Applying these corrections [8], we derived at $Q^2=m_Z^2$

$$\sin^2\bar{\theta}(\nu e) = 0.237\pm0.010_{\mathrm{exp}}\pm0.002_{\mathrm{theor}}\,,$$

$$\bar{\rho}(\nu e) = 1.001\pm0.038_{\mathrm{exp}}\pm0.004_{\mathrm{theor}}\,,$$

[#3] The difference depends on the choice of the top and Higgs masses. In calculations done with the program NUFITTER [8] the masses were fixed to $m_t=150$ GeV, $m_H=100$ GeV.

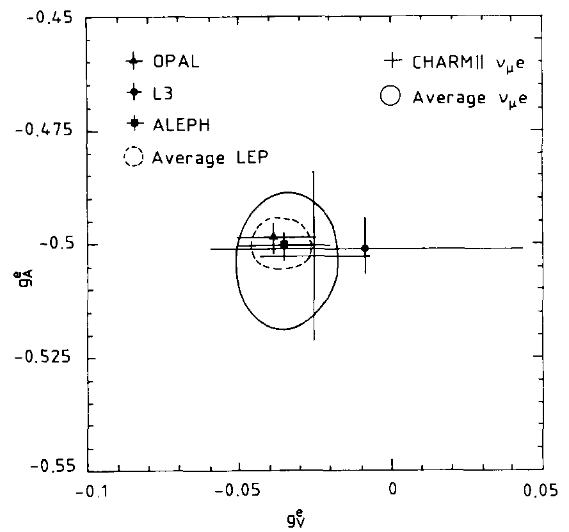

Fig. 2. Comparison of results from neutrino–electron scattering and from $e^+e^- \to e^+e^-$ annihilation at the Z^0 pole in the g_V–g_A plane. The crosses show different experimental data points [1,11,12] and the contours (their projections correspond to one standard deviation) the averages obtained for the two different channels.

where the theoretical error accounts for varying the top quark mass in the range $m_t = 80$–180 GeV and the Higgs boson mass in the range $m_H =$ 50–1000 GeV. This result can be directly compared to the predictions of the minimal standard model using as input parameters α, G_F and the mass measurements of the Z^0 boson performed at LEP [1]:

$$\sin^2\bar{\theta}(\alpha, G_F, m_Z) = 0.233 \pm 0.002_{\text{theor}} ,$$

$$\bar{\rho}(\alpha, G_F, m_Z) = 1.001 \pm 0.004_{\text{theor}} ,$$

with the theoretical errors accounting for the same sources as above. The experimental error from the uncertainty of the Z^0 mass measurement is comparably negligible.

Since the results in terms of $\sin^2\theta$ and ρ are practically uncorrelated we can compare our new result with that previously obtained for $\sin^2\theta$ from the ratio of cross sections [2]. The systematic error due to the absolute neutrino flux and part of the error due to the background subtraction do not influence $\sin^2\theta$ and cancel in the same way for the two-parameter fit as for the cross section ratio. In fact, fixing ρ to unity and leaving the absolute normalization as a free parameter in the fit, the method described above is equivalent to a measurement of the cross section ratio. Using the same data sample (taken in 1987–1989) as in ref. [2] we obtain $\sin^2\theta(\nu e) = 0.236 \pm 0.008 \pm 0.007$, in good agreement with our previous publication. The small difference in the value of $\sin^2\theta^{\nu e}$ arises mainly from a more accurate new calculation of the beam spectra (cf. table 2). The statistical error has been improved by including the information of the differential cross section in the determination of $\sin^2\theta$.

In conclusion, electroweak parameters determined from the differential cross sections of neutrino-electron scattering are in very good agreement with those from LEP experiments. The observed agreement of measurements spanning a factor 10^6 in Q^2 is a remarkable confirmation of the standard model. In future, more data will be included in the analysis and the analysis will be further improved.

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