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Test of the universality of the electron-neutrino and muon-neutrino coupling to the charged weak current

The CHARM Collaboration

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Abstract

A measurement of the ratio of electron-neutrino and muon-neutrino charged-current cross-sections is reported. Using data collected in an exposure of the CHARM detector to a 160 GeV narrow-band neutrino beam at CERN we obtained $\sigma_{\nu_e}(\text{CC})/\sigma_{\nu_\mu}(\text{CC}) = 1.20 \pm 0.11$. A ratio of the coupling constants $g_{e\nu_e}/g_{\mu\nu_\mu} = 1.10 \pm 0.05$ at $\langle Q^2 \rangle \approx 16 \text{ GeV}^2$ was derived in agreement with the universal coupling strength of the electron and muon families to the charged weak current.

The most precise comparison of the coupling strength of the electron and muon to the charged weak current has been derived from measurements of the pion decay rates $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu$ [1], giving

$$g_{e\nu_e}/g_{\mu\nu_\mu} = 0.9939 \pm 0.0057. \quad (1)$$

At larger momentum transfers the ratio may deviate from unity. Direct measurements of the branching ratios $W \rightarrow e\nu_e$ and $W \rightarrow \mu\nu_\mu$ [2] give a first result at $Q^2 = m_W^2$ of

$$g_{e\nu_e}/g_{\mu\nu_\mu} = 1.03 \pm 0.11. \quad (2)$$

A comparison of these coupling constants can also be derived from measurements of the total cross-sections of charged current reactions induced by electron-neutrinos and muon-neutrinos [3]. We are reporting here on a new measurement performed in an exposure of the CHARM detector in a 160 GeV narrow-band beam (NBB) at CERN [4] for events with a mean Q^2 of $\approx 16 \text{ GeV}^2$. Data obtained in this exposure have already been analysed to determine the electroweak mixing angle $\sin^2\theta_W$ from the cross-section ratio of neutral-current (NC) and charged-current (CC) semileptonic interactions of muon-neutrinos [5].

The NBB contains also a small fraction ($\approx 5\%$) of ν_e from K_{e3} decays which can be determined accurately by measuring the relative kaon and pion fluxes. Such a measurement has been performed using a helium-filled differential Cherenkov counter [6], giving $K^+/\pi^+ = 0.1282 \pm 0.0028$. The energy spectrum of electron-neutrinos can be accurately calculated from the well-known K_{e3} decay kinematics, as well as that of muon-neutrinos originating mainly from two-body decays of pions and kaons, and a smaller component from $K_{\mu 3}$ decays.

Selecting muonless events in the detector we obtained a sample composed of NC interactions of muon-neutrinos and electron-neutrinos and of CC interactions of electron-neutrinos. The CC ν_e events have an average visible energy of 87.8 GeV carried by the electron and the hadron showers, whereas the dominant NC ν_μ events and the NC ν_e events, because of the undetected neutrino produced in the interactions, have average visible energies of only 42.3 GeV and 41.6 GeV, respectively. The average radial vertex positions of ν_e and ν_μ events with respect to the beam axis are 79.6 cm and 60.6 cm, respectively.

Because of this marked difference in visible energy and in the position in the detector of ν_e and ν_μ interactions we have been able to separate the events induced by the small ν_e component using a statistical method.

The CHARM neutrino detector has been described in detail before [7]. It consists of a fine-grain calorimeter followed by a muon spectrometer. The calorimeter has a sampling thickness of one radiation length or 0.22 pion absorption lengths, and scintillation counters, proportional drift tubes and streamer tubes as detecting elements. The response of the calorimeter has been calibrated in electron and pion beams with momenta ranging from 0.5 to 140 GeV/c [8]. The energy of hadron showers is measured with a resolution of $\sigma(E)/E = 0.487/\sqrt{E(\text{GeV})} + 0.0127$ and that of electron showers with a resolution of $\sigma(E)/E = 0.18/\sqrt{E(\text{GeV})}$.

Combining the measurements of showers in all detection elements the lateral vertex position of hadron showers is determined; above 50 GeV, where the CC ν_e events cluster, the precision is better than 3 cm. For this experiment the fiducial target volume extended over 55 target plates; five plates have been used at the beginning of the detector to reject incoming tracks and 18 plates at the end to measure the shower energy. The fiducial target had a mass of 87 tons.

The calorimeter is surrounded by a magnetized iron frame to deflect back into the calorimeter muons that would otherwise leave the detector. The muon spectrometer at the end is of the magnetized iron type with a toroidal magnetic field and proportional drift tubes as track detectors.

Details of the data acquisition and the trigger efficiency have been described already [5]. The interactions in the CHARM detector were classified by an automatic pattern-recognition program on an event-by-event basis. Neutrino interactions are defined generically as events without entering charged tracks. A neutrino event is classified as a ν_μ induced CC interaction if a muon of more than 1 GeV is originating from the event vertex. All other neutrino-event candidates were classified as muonless. The classification efficiency of this automatic pattern-recognition has been checked by visual inspection of 20,000 randomly selected events and 4000 events with topologies for which the program code could fail. The efficiency for events with energy larger than 4 GeV was found to be greater than 99.98%. The classification errors on the two event classes were found to be $\pm 0.1\%$ after correcting for the small inefficiencies.

The event numbers of the two classes thus obtained have to be corrected for background and for losses. The background due to cosmic-rays was experimentally determined by using data taken outside the beam spill. Events due to the so-called wide-band beam (WBB) 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 iron absorber and subtracted. Events induced by CC ν_μ interactions in which the primary muon cannot be identified are classified as muonless. Some of these lost events have muons with an energy of less than 1 GeV; another contribution is caused by muons leaving the sides of the detector or being obscured by the hadronic shower. This is the largest correction, amounting to 3.5% of all CC ν_μ events, and must therefore be made in a reliable way. In a previous publication [5] we have shown, by two independent methods, that this can be achieved to within 2% of the correction.

A small fraction of the muonless and therefore also of the ν_e induced events contains a track which fulfils the requirements of a primary muon of a CC ν_μ event; these events are classified as CC ν_μ events. This background is caused by decays of pions or kaons which are part of the shower or by non-interacting, so-called punch-through, hadrons. The correction was evaluated from the data sample which has two tracks which satisfy the muon recognition criteria. In table 1 the corrections to the data are summarized for hadron energies larger than 4 GeV; details are given in a previous publication [5]. We found 106121 ± 408 muonic events and 35131 ± 274 muonless events.

Figure 1a shows the shower energy distribution of the muonless event sample. We have chosen the variable $\sqrt{E}$ to ensure approximate independence from resolution effects. The contribution of events due to ν_e interactions produces a shoulder. The main contribution due to ν_μ NC interactions is shown separately, as predicted by a Monte Carlo simulation. Figure 1b shows the radial distribution of ν_μ and ν_e induced muonless events.

The physics analysis, aimed at separating ν_e and ν_μ induced interactions on a statistical basis, exploited the differences which are apparent in fig. 1. The muonless event sample was sorted into cells of the parameter space $[\sqrt{E}, r]$ with the dimensions of $0.5 (\text{GeV})^{1/2} \times 20 \text{ cm}$. Each generic cell has contributions from CC ν_e , NC ν_e , and NC ν_μ , the respective numbers of events to be determined. The fractional contributions of CC ν_e and NC ν_e events to each cell have been determined by simulation using Monte Carlo methods. The fractional contribution of NC ν_μ events to each cell was derived

from the CC ν_μ events. The Monte Carlo simulation was used in this case to correct for the different y distributions of CC ν_μ and NC ν_μ events, thus reducing the systematic errors due to the uncertainties in the beam spectra, in the detector response.

The simulation of deep inelastic neutrino interactions was based on a quark-parton model description of the nucleon [9], and included radiative effects [10] and the different response of the calorimeter to electromagnetic and hadronic energy, in the ratio of 1.17 [8]. In the case of CC ν_e interactions elastic and quasi-elastic interactions were also simulated.

The y distribution of deep inelastic neutrino scattering by NC or CC interaction was described by a constant part, with a coefficient $(1 - \alpha)$ and a part proportional to $(1 - y)^2$ with a coefficient α [11],

$$d\sigma/dy = A[(1 - \alpha) + \alpha(1 - y)^2]. \quad (3)$$

The coefficient α^{CC} was derived from measured y distributions of ν_μ and $\bar{\nu}_\mu$ induced CC interactions [12], from the cross-sections and x distributions of ν_μ and $\bar{\nu}_\mu$ dimuon events [13], and from the measurements of semileptonic decays of charmed particles [14]. The coefficient α^{NC} was derived from $\alpha_{\nu_\mu}^{\text{CC}}$ and $\alpha_{\bar{\nu}_\mu}^{\text{CC}}$, and the value of $\sin^2\theta_w$ determined from leptonic ν_μ and $\bar{\nu}_\mu$ scattering [15]. We thus avoided making any assumptions on the ratio of deep inelastic ν_μ and ν_e cross-sections and found the following values

$$\alpha^{\text{CC}} = 0.11 \pm 0.04 \quad (4a)$$

$$\alpha^{\text{NC}} = 0.19 \pm 0.04. \quad (4b)$$

The values of α^{CC} and α^{NC} are correlated because NC interactions are dominated by scattering on left-handed quarks.

The quality of the simulation has been verified by comparison with ν_μ induced CC interactions. Forming 168 cells in the parameter space $[\sqrt{E}, r]$ the best fit gave $\chi^2/\text{DF} = 1.07$. The measured and simulated distributions projected onto $\sqrt{E}$ and r are shown in figs. 2a and 2b. The agreement is excellent and confirms the validity of the simulation.

From the best fit of 168 cells of muonless events in the parameter space $[\sqrt{E}, r]$ we found [16]

$$N_{\nu_e}^{CC} = 2251 \pm 184 \text{ (stat.)} \pm 63 \text{ (syst.)} \quad (E_\nu \geq 4 \text{ GeV}) \quad (5a)$$

$$N_{\nu_e}^{NC} = 575 \pm 386 \text{ (stat.)} \pm 114 \text{ (syst.)} \quad (E_h \geq 4 \text{ GeV}). \quad (5b)$$

and a χ^2/DF of 0.9. The statistical errors were derived from the contour corresponding to one unit variation of χ^2 in varying both $N_{\nu_e}^{CC}$ and $N_{\nu_e}^{NC}$. Figures 3a and 3b show the measured and calculated best-fit distributions for the projections $\sqrt{E}$ and r . We verified that the results are stable with respect to changes of the region of $[\sqrt{E}, r]$ and to variations of the size of the cells.

Normalizing the number of ν_μ induced CC events to the ν_e flux and energy spectrum we would have detected 1874 ± 76 CC ν_e events in a beam of equal ν_e and ν_μ fluxes. The error includes the uncertainties in the relative amounts of kaons and pions in the parent beam (3%), in the event acceptance, and in the normalization. We then obtained the ratio

$$\sigma_{\nu_e}^{(CC)}/\sigma_{\nu_\mu}^{(CC)} = 1.20 \pm 0.11, \quad (6)$$

where statistical and systematic errors have been combined in quadrature.

From eq. (5), we obtained the ratio of the NC and CC ν_e cross-sections for deep inelastic scattering with hadronic energy larger than 4 GeV

$$R_{\nu_e} = \sigma_{\nu_e}^{(NC)}/\sigma_{\nu_e}^{(CC)} = 0.27 \pm 0.19. \quad (7)$$

We applied a correction to the number of CC ν_e events to account for the difference in the neutrino energy E_ν and the hadronic energy E_h . The error also takes into account the correlations between the measured values of $N_{\nu_e}^{CC}$ and $N_{\nu_e}^{NC}$.

In calculating the event numbers $N_{\nu_e}^{CC}$ and $N_{\nu_e}^{NC}$ we have taken into account systematic uncertainties in the following quantities: 1) the NBB momentum, 2) the values of α^{NC} and α^{CC} , 3) the y distribution of ν_e induced NC events, 4) the energy calibration of the response of the calorimeter to electromagnetic showers and 5) the radiative corrections. We varied the values of the relevant parameters and found the contributions to N_{ν_e} and R_{ν_e} summarized in table 2.

From the cross-section ratio [eq. (6)] we deduced a ratio of the coupling strengths to the charged weak current at $Q^2 \approx 16 \text{ GeV}^2$ of

$$g_{e\nu_e}/g_{\mu\nu_\mu} = [\sigma_{\nu_e}(\text{CC})/\sigma_{\nu_\mu}(\text{CC})]^{1/2} = 1.10 \pm 0.05, \quad (8)$$

in agreement with the notion of universality and with previous measurements [1-3].

The ratio of NC and CC cross-sections of ν_e induced reactions [eq. (7)] agrees, within the large errors, with $R_{\nu_\mu} = 0.3093 \pm 0.0031$ [5] determined by this Collaboration from the same set of data. We prefer to quote the more accurate value of R_{ν_e} determined by this Collaboration in the enriched ν_e beam from a proton beam dump, and to combine these results [17].

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Table 1

arXiv:1404.1001v1 [hep-ex]

Neutrino event numbers (shower energy $E \geq 4$ GeV)

	Muonless	Charged-current ν_μ
Uncorrected data sample	39239 ± 198	108472 ± 329
Efficiency correction	7 ± 4	0
Scan correction	40 ± 40	60 ± 44
WBB and cosmic correction	-2310 ± 87	-4311 ± 119
Difference in energy cut	0	0 ± 129
Lost muons	-3737 ± 105	3735 ± 105
π and K decay	-1892 ± 50	-1835 ± 50
Corrected event numbers	35131 ± 274	106121 ± 408

Table 2

Systematic uncertainties in the determination of $N_{\nu_e}^{\text{CC}}$ and R_{ν_e}

Source	Parameter variation	$\Delta N_{\nu_e}^{\text{CC}}$	ΔR_{ν_e}
Parent beam energy	156-160 GeV	± 16	± 0.02
y distribution of ν_μ NC and CC events	$0.07 < \alpha^{\text{CC}} < 0.15$		
	$0.15 < \alpha^{\text{NC}} < 0.23$	± 16	± 0.01
y distribution of NC ν_e events	$0.1 < \alpha_{\nu_e}^{\text{NC}} < 0.8$	± 53	± 0.01
Electromagnetic energy calibration	$\pm 2\%$	∓ 19	± 0.04
Radiative corrections	$\pm 20\%$	± 18	± 0.01

Figure captions

- Fig. 1 Experimental distributions (a) of the muonless events as a function of the square root of the shower energy $\sqrt{E}$, and (b) of the radial vertex position r of the neutrino interactions in the calorimeter with respect to the beam axis. The solid lines and the dashed regions represent the expected contributions of ν_μ and ν_e events. The ν_e events produce a shoulder in the $\sqrt{E}$ distribution.
- Fig. 2 Experimental distributions (a) of the CC ν_μ events as a function of the square root of the shower energy $\sqrt{E}$, and (b) of the radial vertex position r of the neutrino interactions in the calorimeter with respect to the beam axis. The solid lines represent the results of a Monte Carlo simulation normalized to the data.
- Fig. 3 Experimental distribution (a) of the muonless events as a function of the square root of the shower energy $\sqrt{E}$, and (b) of the radial vertex position r of the neutrino interactions in the calorimeter with respect to the beam axis. NC ν_μ events as determined by the fit have been subtracted. The solid lines show the expected distributions of the sum of electron-neutrino induced NC and CC events obtained from the fit. The dashed line in Fig. 3a represents the distribution of NC ν_e events.

Fig. 1

Fig. 2

Fig. 3