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Evidence for Neutral Neutrino Current Coupling to Right-handed Quarks

The CHARM Collaboration

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Differential cross sections $d\sigma/dy$ have been measured in semileptonic neutral- and charged-current reactions induced by neutrinos and antineutrinos. The comparison of the neutral- and the charged-current differential cross sections allows the direct determination of the chiral coupling of the neutral ($\nu\bar{\nu}$) current to left- and right-handed quarks. The result, with a value of $g_R^2 = 0.042 \pm 0.010$, is the first direct determination, with a significance of more than four standard deviations, of a non-zero value of g_R .

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In a systematic study of *neutral* current interactions the CHARM collaboration has recorded high statistics data on interactions of neutrinos and antineutrinos on nucleons in a 160 GeV narrow band beam. Results on total cross sections and on ratios of cross sections, giving a precise value of the electroweak mixing angle, were already published [1,2]. In another publication[3] the differential cross sections, $d\sigma/dx$, in the Bjorken scaling variable for neutral- and charged-current interactions were reported and the universality of the nucleon structure, as probed by weak neutral- and charged-current interactions and by the electromagnetic current, has been confirmed. In this paper we present differential cross sections $d\sigma/dy$ in the inelasticity y for deep inelastic neutrino- and antineutrino-nucleon scattering induced by charged-current coupling,

$$\nu_\mu(\bar{\nu}_\mu) N \longrightarrow \mu^-(\mu^+) X \quad (\text{CC})$$

and by neutral-current coupling,

$$\nu_\mu(\bar{\nu}_\mu) N \longrightarrow \nu_\mu(\bar{\nu}_\mu) X \quad (\text{NC}).$$

An earlier publication on this subject [4] was based on a much smaller statistical sample.

The inelasticity, defined as the ratio $y = E_h/E_\nu$ of the energy E_h of the hadronic final state X and the neutrino energy E_ν , is related to the scattering angle in the elementary neutrino-quark interactions. The differential cross sections $d\sigma/dy$ for both NC and CC events are directly related to the space-time structure of the weak currents involved; they give the admixture of vector (V) and axial-vector (A) couplings and may also indicate the presence of any scalar (S) or pseudoscalar (P) terms. They yield information on the relative antiquark sea contents of the nucleon. In this paper we investigate the helicity dependence of the neutral weak neutrino current coupling and assume V and A interactions only.

In the standard model the neutral current is predicted to have a more complex helicity structure than the charged current, known to be of V-A structure. Owing to the unified electroweak force the $(\nu\bar{\nu})$ current can interact both with left-handed fermions and with right-handed fermions, in the same way as the electromagnetic current. The weak mixing angle θ_w determines the relative strength of the coupling to left-handed (g_L) and right-handed fermions (g_R). Assuming this structure values of the coupling of right-handed quarks have been derived from measurements of scalar quantities (cross sections) [5]. The y -distributions measured in this experiment can be used to demonstrate directly the coupling of the neutral current to the right-handed quarks in the nucleon. "You need a nut to find the sense of a screw" [6].

The angular distribution of the elementary $\nu(\bar{\nu})$ quark scattering process is composed of two components, an isotropic one ($J = 0$) for $\nu_L q_L$ and $\bar{\nu}_R q_R$ scattering and an anisotropic $(1 - y)^2$ component ($J = 1$) for $\nu_L q_R$ and $\bar{\nu}_R q_L$ scattering. Because of the polarization of the neutrinos the y -distributions are therefore sensitive to the relative coupling of left- and right-handed quarks in the nucleon. By comparison of neutral- and charged-current y -distributions the coupling of neutral currents to right-handed quarks can be extracted. C. H. Llewellyn Smith [7] has derived a fundamental relation between NC and CC differential cross sections of $\nu(\bar{\nu})$ on isoscalar targets:

$$\begin{aligned} \left(\frac{d\sigma}{dy}\right)_{NC}^{\nu} &= g_L^2 \left(\frac{d\sigma}{dy}\right)_{CC}^{\nu} + g_R^2 \left(\frac{d\sigma}{dy}\right)_{CC}^{\bar{\nu}} \\ \left(\frac{d\sigma}{dy}\right)_{NC}^{\bar{\nu}} &= g_L^2 \left(\frac{d\sigma}{dy}\right)_{CC}^{\bar{\nu}} + g_R^2 \left(\frac{d\sigma}{dy}\right)_{CC}^{\nu} \end{aligned}$$

This relation is valid for nucleons composed of u and d quarks (and $\bar{u}$ and $\bar{d}$ antiquarks) only, and its validity depends on the assumption of weak isospin invariance.

The relation allows the separate determination of the coupling constants g_L^2 and g_R^2 from the four y -distributions (NC and CC, ν and $\bar{\nu}$), without having to assume a specific parametrization of the distributions as a function of y .

In neutral-current (NC) events the energy E_l' of the outgoing lepton cannot be measured. Thus the incoming neutrino energy E_ν cannot be reconstructed by adding the measured hadronic energy E_h and the energy E_l' . For charged-current (CC) events this is possible with a measurement of the outgoing muon energy. The determination of the differential cross section $d\sigma/dy$ for NC events has to rely on measuring the hadron energy E_h and the distance r of the event vertex from the beam axis and therefore requires an unfolding procedure, resorting to the knowledge of the incoming neutrino energy spectrum and its radial dependence. As a test of this statistical procedure we determined the differential cross section $d\sigma/dy$ for CC events in the same way, thus neglecting the measurement of the muon momentum and using the final state muon in the CC events solely for event classification. Furthermore, the use of the same technique in the NC and CC data reduces possible systematic error contributions in the comparison, as explained in more detail below.

The experiment was performed with the CHARM neutrino detector in the CERN 160 GeV narrow band neutrino beam. A description of the beam layout and monitoring as well as details about the detector can be found in earlier publications [1-3]. Briefly, 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 an rms momentum spread of $\pm 6\%$. The relative amount of pions and kaons in the beam was measured using a Helium-filled differential Cherenkov counter. At any fixed distance r (radius) of the interaction vertex from the beam axis in the detector, the neutrino-energy spectrum has two peaks caused by the presence of neutrinos from both pion and kaon decays. The knowledge of all the beam parameters allows the neutrino flux $\Phi(E_\nu, r)$ to be calculated as a function of the neutrino energy E_ν and of the radius r in the detector. The interaction vertex of a neutral current event is measured with a typical resolution of about 3 cm in the CHARM detector. This accuracy allows the radius-energy relationship in the narrow-band beam to be used, which is essential for the determination of the differential cross section $d\sigma/dy$ without a measurement of the outgoing lepton energy.

The detector is a fine-grain marble calorimeter, followed by an iron spectrometer with a toroidal magnetic field; it is surrounded by a magnetized iron frame, both for the identification of muons and for their momentum measurement. The calorimeter had a sampling step corresponding to one radiation length or 0.22 absorption length; scintillators, proportional drift tubes and streamer tubes were used, as described elsewhere [8]. The response of the calorimeter to hadron showers (and electrons) was calibrated in pion and electron beams from 0.5 to 140 GeV/c [9]. The energy of hadron showers is measured by the scintillators with a resolution of $\sigma(E_h)/E_h = 0.49/(E_h/\text{GeV})^{1/2} + 0.013$.

In total about 140 000 neutrino induced events have been recorded in the neutrino and in the antineutrino exposures. The events selected for this analysis have more than 4 GeV hadronic shower energy and do not have a visible entering track. A fiducial volume of ± 120 cm with respect to the beam axis and extending over 55 target plates was used, leaving 5 plates before the vertex to reject events with incoming tracks and 18 plates at the end to ensure sufficient shower containment; it corresponded to a target mass of 69 tonnes.

The distinction between NC and CC events is based on the computer reconstruction of a muon

	Neutrino		Antineutrino	
	NC	CC	NC	CC
Raw data	35954	101418	2108	5170
Wide band beam, cosmics	-1759	-3779	-236	-378
CC, unidentified muon	-3391	+3391	-36	36
NC with decay muon	+1709	-1709	+94	-94
K_{e3} beam contribution	-1943	-119	-66	-3
Corrected data	30570	99202	1864	4731

Table 1: Raw event numbers with shower energy > 4 GeV and radius < 120 cm, and corrected event numbers.

y -interval	ν CC	$\bar{\nu}$ CC	ν NC	$\bar{\nu}$ NC
0.05 - 0.15	0.740 $\pm$ 0.018	0.594 $\pm$ 0.046	0.231 $\pm$ 0.010	0.201 $\pm$ 0.025
0.15 - 0.25	0.720 $\pm$ 0.020	0.576 $\pm$ 0.046	0.233 $\pm$ 0.011	0.198 $\pm$ 0.028
0.25 - 0.35	0.728 $\pm$ 0.023	0.408 $\pm$ 0.048	0.230 $\pm$ 0.011	0.224 $\pm$ 0.033
0.35 - 0.45	0.768 $\pm$ 0.021	0.371 $\pm$ 0.045	0.215 $\pm$ 0.013	0.125 $\pm$ 0.027
0.45 - 0.55	0.683 $\pm$ 0.021	0.287 $\pm$ 0.042	0.227 $\pm$ 0.012	0.094 $\pm$ 0.026
0.55 - 0.65	0.676 $\pm$ 0.026	0.273 $\pm$ 0.039	0.221 $\pm$ 0.013	0.136 $\pm$ 0.026
0.65 - 0.75	0.640 $\pm$ 0.024	0.169 $\pm$ 0.034	0.184 $\pm$ 0.013	0.090 $\pm$ 0.023
0.75 - 0.85	0.622 $\pm$ 0.040	0.182 $\pm$ 0.030	0.206 $\pm$ 0.020	0.059 $\pm$ 0.021
0.85 - 1	0.596 $\pm$ 0.079	0.106 $\pm$ 0.024	0.162 $\pm$ 0.024	0.056 $\pm$ 0.015

Table 2: Differential cross sections $d\sigma/dy$ in units of $G^2 m_p E_\nu/\pi$.

in the event, close to the interaction point and with a range exceeding an energy loss of 1 GeV. Details of the selection criteria, the background corrections and contributions or losses due to misidentification are given elsewhere [2]. The event numbers and corrections are summarized in Table 1. All contributions were taken into account in the unfolding procedure.

The differential cross sections $F(y) = d\sigma/dy$, in units of $G^2 m_p E_\nu/\pi$, were determined from the measured data with a procedure for regularized unfolding [10], which has already been applied to several similar problems. In the present analysis it is based on the two-dimensional histogram $g(E_h, r)$ of the measured values of the hadronic energy E_h and the radius r of the interaction vertex w.r.t. the beam axis. This measured histogram is related to the differential cross section $F(y)$ by an integral equation

$$g(E_h, r) = \int R(E_h, r, y) \cdot F(y) dy + B(E_h, r),$$

where $R(E_h, r, y)$ is the resolution function of the experiment, and $B(E_h, r)$ are background contributions to the measured histogram. In this equation the function $F(y)$ is the unknown and has to be determined from the measured histogram $g(E_h, r)$, using the known resolution function and the known background contributions (either measured or calculated). The resolution function is not known as an explicit function, but is implicitly described by a set of simulated (Monte Carlo) events, for which the y -value of each event is known. In the event simulation, details of the detector response and of the beam flux $\Phi(E_\nu, r)$ determine the distribution in E_h and r for any given value of y . The unfolding procedure (for details of the mathematical treatment see ref. [10]) used as input sets of measured and simulated events and reconstructed binned values for the distribution $F(y)$ with a full covariance matrix for the binned values. For practical reasons the variables $h = \sqrt{E_h}$ and radius r were used in the unfolding. The resolution in h corresponds to an almost constant

value of $\sigma(h) \approx 0.25\sqrt{GeV}$.

The Monte Carlo program described below was used to generate the simulated events, which were required for the unfolding. Although in the Monte Carlo program events were generated according to an algorithm based on the quark parton model and taking into account all details of e.g. thresholds in the invariant mass, which depend on the quark content of the reaction, this aspect is unimportant for the unfolding, because the resulting $d\sigma/dy$ does not depend on the input y -distribution. The only aspect essential for the unfolding is the detector simulation, which is based on the known resolution properties of the detector. In the case of CC events, the effects of real bremsstrahlung were taken into account in the simulation. The unfolding procedure was tested on charged-current events, where a comparison with the distribution $d\sigma/dy$ determined by using the muon measurements is possible.

The results of the unfolding are shown in figure 1 for charged-current and figure 2 for neutral-current reactions, for both ν and $\bar{\nu}$ data; the cross-section values are given in Table 2. Electroweak radiative corrections have been applied to the data [11]; they amount to up to 3 % for single y -bins in the case of the CC data and are smaller in the case of the NC data. The errors given in figures 1 and 2 are derived from the diagonal elements of the covariance matrix. In the fits described below the complete covariance matrix was used. It accounts also for correlations between the different bins in the distribution due to the finite detector resolution. Additional error contributions are due to the uncertainties of the K/π ratios 0.1360 ± 0.0040 and 0.0687 ± 0.0032 for neutrino and antineutrino beams, respectively, and to the $\pm 1\%$ uncertainty in the overall factor for the hadron energy calibration of the calorimeter; they introduce correlations between the different distributions. To take into account possible uncertainties in the detector resolutions, all errors were multiplied by an additional factor of 1.25 (this factor reduces the ratio $\chi^2/(\text{number of degrees of freedom})$ in the fit described below to 1.0). Uncertainties due to acceptance limitations in the hadronic energy and the muon momentum and corrections of NC/CC misidentifications are largest for y close to zero and one. The lowest y -bin ($y < 0.05$) is therefore excluded, and the last bin is made wider ($y > 0.85$).

The curves shown in figures 1 and 2 give the results of calculations based on a quark parton model. Theoretically the expected y -dependence has a simple mathematical dependence. At our energies however this simple dependence is not exactly valid because of threshold effects. Quark fragmentation in the final state of deep inelastic neutrino scattering leads to thresholds in the invariant mass, which depend on the quark content in the reaction. The muon mass has been explicitly taken into account for the CC reactions. We described the strange-quark sea using experimental data on neutrino-induced di-muon production, and used $\bar{s}/d_v = 0.06 \pm 0.02$, and parametrized the x dependence of the strange sea as in ref. [1]. We applied corrections for the charm-quark sea assuming $c/s = 0.2 \pm 0.2$ as derived from dimuon production by deep inelastic muon scattering [12]. In flavour-changing reactions ($d \rightarrow c$, $s \rightarrow c$) the kinematical threshold effects were described by the c -quark mass m_c using the slow rescaling model [13] with a fixed value of $m_c = 1.5 GeV/c^2$. Finally we added a term for effects due to the longitudinal structure function F_L , using a parametrization consistent with QCD predictions and with available measurements [14]. In addition a small correction for non-isoscalarity of the target has been made.

The result of the fit to the data is

$$g_L^2 = u_L^2 + d_L^2 = 0.287 \pm 0.008$$

$$g_R^2 = u_R^2 + d_R^2 = 0.042 \pm 0.010,$$

with a correlation coefficient between the two values of -0.79 . The value of g_R^2 demonstrates for the first time directly the existence of a non-vanishing coupling of the $(\nu\bar{\nu})$ current to right-handed quarks with a significance of more than four standard deviations. The values of g_L^2 and g_R^2 reported here are in good agreement with the values predicted by the standard model for $\sin^2\theta_w = 0.236$ ($g_L^2 = 0.295$ and $g_R^2 = 0.031$) and with the compilation of results derived from cross section measurements [5].

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Figure 1: The differential cross section $d\sigma/dy$ of ν and $\bar{\nu}$ induced deep inelastic charged-current processes after resolution unfolding and acceptance and radiative corrections (in units of $G^2 m_p E_\nu / \pi$). The curves are explained in the text.

Figure 2: The differential cross section $d\sigma/dy$ of ν and $\bar{\nu}$ induced deep inelastic neutral current processes after resolution unfolding and acceptance corrections (in units of $G^2 m_p E_\nu / \pi$). The curves are explained in the text.