EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-37
22 March 1985

MEASUREMENT OF THE CROSS SECTION OF COHERENT π^0 PRODUCTION BY MUON NEUTRINO
AND ANTINEUTRINO NEUTRAL-CURRENT INTERACTIONS ON NUCLEI

CHARM Collaboration

F.Bergsma and J.Dorenbosch
NIKHEF, Amsterdam, The Netherlands

J.V.Allaby, U.Amaldi, G.Barbiellini¹⁾, W.Flegel,
L.Lanceri, M.Metcalf, C.Nieuwenhuis, J.Panman, C.Santoni²⁾ and K. Winter
CERN, Geneva, Switzerland

I.Abt, J.Aspiazu, F.W.Büsser, H.Daumann, P.D.Gall, T.Hebbeker,
F.Niebergall, P.Schütt, and P.Stähelin
II. Institut für Experimentalphysik³⁾, Universität Hamburg, Hamburg, Germany

P.Gorbunov, E.Grigoriev, V.Khovansky and A.Rosanov
Institute for Theoretical and Experimental Physics, Moscow, USSR

A.Baroncelli⁴⁾, L.Barone⁵⁾, B.Borgia⁵⁾, C.Bosio⁴⁾, A.Capone⁵⁾, M.Djemoz⁵⁾,
U.Dore⁵⁾, F.Ferroni⁵⁾, E.Longo⁵⁾, L.Luminari⁵⁾, P.Monaçelli⁵⁾,
F.de Notaristefani⁵⁾, L.Tortora⁴⁾ and V.Valente⁶⁾
Istituto Nazionale di Fisica Nucleare, Rome, Italy

(Submitted to Physics Letters B)

-
- ¹⁾ On leave of absence from INFN, LN Frascati, Italy.
²⁾ On leave of absence from INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.
³⁾ Supported by Bundesministerium für Forschung und Technologie, Bonn, German Federal Republic.
⁴⁾ INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.
⁵⁾ Dipartimento di Fisica, Università "La Sapienza", Roma and INFN Sezione di Roma, Rome, Italy.
⁶⁾ Laboratori Nazionali INFN Frascati, Italy.

ABSTRACT

Measurements of coherent π^0 -production by muon-neutrinos and antineutrinos on nuclei in marble have been carried out using the CHARM-neutrino detector in the CERN-SPS neutrino wide-band beam. We determined the cross sections $\sigma_\nu=(96\pm42)*10^{-40}$ cm² and $\sigma_{\bar{\nu}}=(79\pm26)*10^{-40}$ cm² per average marble nucleus. Comparing these experimental results to theoretical predictions we evaluated the isovector axialvector neutral current coupling constant $|\beta|=1.08\pm0.24$, averaged over the neutrino and the antineutrino results, and found agreement with the prediction of the standard model, $\beta=1.0$. From the ratio of coherent π^0 production by neutral current interactions observed in this experiment and of coherent π^- production by charged-current interactions of antineutrinos measured in BEBC a value of $|\beta|=1.10\pm0.23$ is derived.

Coherent π^0 production by neutral-current neutrino interactions on a nucleus with mass number A probes directly the isovector axialvector part of the electroweak interaction, owing to the intrinsic quantum numbers of neutral pions. Calculations of this process

$$(\bar{\nu})_{\mu} + A \rightarrow (\bar{\nu})_{\mu} + A + \pi^0$$

were carried out by Nachtmann and Lackner [1,2] and later by Rein and Sehgal [3]. Measurements at mean energies of 2 GeV at the CERN-PS were published by the Aachen-Padua group [4] and by the Gargamelle Bubble Chamber group [5]. The corresponding charged-current reaction $\bar{\nu}_{\mu} + A \rightarrow \mu^+ + A + \pi^-$ has been studied in BEBC [6].

The coherent π^0 -production is characterized by a constructive interference of the neutrino interactions on neutrons and protons within a single nucleus. The nucleus itself does not break up in this reaction and therefore a negligible amount of recoil energy is transferred to it. Coherently produced π^0 's are emitted at small angles compared to those produced in the incoherent and resonant π^0 -production; they are the main background in experiments studying elastic muon-neutrino (antineutrino) scattering off electrons [7,8,9]. Coherent η^0 production probing the isoscalar axialvector part of the electroweak interaction is predicted not to exist. This prediction cannot be checked in this experiment because the detection efficiency for η^0 is negligibly small.

The predicted cross section for coherent π^0 production is proportional to the factor

$$(u_a - d_a)^2 \rho^2 \tag{1}$$

where u_a and d_a are the axialvector coupling constants of u and d quarks, respectively, and ρ the ratio of the neutral- and charged-current coupling constants. The standard model predicts $u_a = -d_a = 1/2$ and $\rho = 1$ so that a value of 1 is expected for expression (1).

In this experiment we determine the absolute value of the difference of u_a and d_a , i.e. the isovector axialvector coupling $|\beta| = |u_a - d_a|$, by comparing the measured cross-section with the calculated value, assuming $\rho = 1$ as suggested by other measurements [10]. Because of the pure axialvector nature of the process the cross sections of the neutrino and antineutrino induced reactions are expected to be equal.

Many experiments are sensitive only to the absolute values of u_a, d_a . They are found to agree with the theory [10]. The measurement of $|\beta|$ allows then a determination of the relative sign of u_a and d_a . Previously this sign

has been deduced from an analysis of elastic νp scattering and Δ production [11].

Data have been collected in an exposure of the fine-grained calorimeter of the CHARM-Neutrino Detector [12] to the horn focused wide-band neutrino beam of the CERN 400 GeV Super Proton Synchrotron (SPS). The spectrum of the neutrino (antineutrino) beam was computed using a simulation program developed at CERN [13]. It was found to agree with the spectrum derived from the measured energy distribution of muons produced in quasielastic neutrino interactions [14]. The average neutrino and antineutrino energies were 31 GeV and 24 GeV, respectively. In two exposures with $1.4 \cdot 10^{18}$ and $5.7 \cdot 10^{18}$ protons on target, $1.3 \cdot 10^6$ neutrino interactions and $1.4 \cdot 10^6$ antineutrino interactions, respectively, were observed in the 80 t fiducial mass of the detector. The target calorimeter consisted of 78 subunits. A subunit comprised a marble plate of $3 \times 3 \text{ m}^2$ surface area and 8 cm thickness, followed by two planes of sensitive elements: (i) 128 proportional drift tubes, each tube having dimensions of $3 \times 3 \times 400 \text{ cm}^3$, and (ii) 20 plastic scintillators of dimensions $15 \times 3 \times 300 \text{ cm}^3$. A subunit was one radiation length thick. The target calorimeter was followed by four toroidal iron magnets, serving as muon spectrometer. For part of the exposure the detector was equipped with streamer-tubes [15] with wires oriented at 90° with respect to the proportional tubes.

The method to extract the coherent π^0 candidates followed closely the procedure used in the previously published analysis of $(\bar{\nu})_\mu e$ -scattering [7,8,9]. We selected events with narrow electromagnetic showers initiated by a single electron or $\gamma(\pi^0)$ by applying the following criteria:

1. All charged-current semileptonic events with a muon track candidate longer than 8 radiation lengths were rejected.
2. The fiducial volume was restricted to an area of $2.3 \times 2.3 \text{ m}^2$ and a length corresponding to 60 marble planes extending from plane 3 to 63.
3. The visible energy was required to be larger than 6 GeV and less than 20 GeV. The lower energy cut was determined by the requirement of full trigger efficiency, whereas above 20 GeV we expected a less favourable signal to background ratio.
4. The length of the shower was required to be in the range of 84 cm to 164 cm: hadronic background is reduced by 32% and electromagnetic showers are selected with 98% efficiency.

5. The estimator which discriminated best between electromagnetic and hadronic showers was based on their different widths. The lateral shower profile was measured in the vertical and horizontal planes by the scintillator hodoscopes. The width Γ of a Cauchy distribution fitted to the central part of the shower was calculated. A second parameter Δ using measurements by the proportional drift tubes was obtained by comparing the energy deposited in tubes further away than 6 cm from the shower axis to the total shower energy [16]. These estimators depend only weakly on the shower energy and angle and were calibrated by measurements in a beam of pions and electrons from 5 GeV up to 50 GeV. Fig.1 shows the distributions found at 15 GeV. Events were selected if $\Gamma < 0.8$ cm and $\Delta < 0.3$. Since a π^0 beam is not available, the π^0 acceptance of these cuts has been calculated. The Electron-Gamma-Simulation program (EGS) [17] predicts an electron acceptance of 90% in accordance with experimental data and an acceptance of 79% for π^0 . Hadronic background is rejected by a factor larger than 100.
6. The hadronic events remaining in the sample were further rejected by the requirement of a single hit in the first tube plane after the vertex. This requirement improves also the angular resolution.

The combined selection efficiency for π^0 -candidates using criteria 4, 5 and 6 is $\varepsilon_{\text{tot}} = (48 \pm 4)\%$, for hadronic showers it is $\varepsilon < 1\%$.

The analysis was performed in the variable $E\theta^2$ because the shape of the coherent signal distribution is energy independent in that representation. E denotes the measured energy of the π^0 shower and θ its angle to the neutrino beam axis. 627 neutrino events and 1328 antineutrino events were selected with $E\theta^2 < 220$ MeV. 90% of the coherent π^0 events are expected to have $E\theta^2 < 100$ MeV. We estimated the background in the $E\theta^2$ region from 100 MeV to 220 MeV and extrapolated it into the region $E\theta^2 < 100$ MeV. We assumed 3 sources of background (see fig.2):

1. Neutrino-electron scattering
2. Quasielastic charged-current events induced by the ν_e and $\bar{\nu}_e$ contamination of the beam
3. Incoherent and resonant π^0 production [3,18] and hadronic (NC) events with a large electromagnetic component

The accepted $E\theta^2$ interval was divided into 4 regions:

- F = Forward region with $E\theta^2 < 9$ MeV (contains all 3 background sources plus signal)
- M = Main region with $9 \text{ MeV} < E\theta^2 < 100$ MeV (contains background two and three plus signal)
- Two background regions
 - a) B1 with $120 \text{ MeV} < E\theta^2 < 170$ MeV
 - b) B2 with $170 \text{ MeV} < E\theta^2 < 220$ MeV

which contain the background sources two and three.

The background region was divided into two different $E\theta^2$ bins to determine the slope of the background. The events in region M were separated into two categories, electron-induced and γ - or π^0 - induced showers according to the energy deposition observed in the first scintillator plane after the vertex (E_{first}), which was used to discriminate between them. Fig.3a shows the E_{first} distribution for quasielastic ν_e events determined by using observed $(\bar{\nu})_\mu$ induced events and replacing the muon by an electron with the help of a Monte Carlo (EGS) simulation of the detector. In fig.3b the distribution calculated for coherently produced π^0 is shown. The number of events attributed to electron-induced background is obtained from the number of events with $E_{\text{first}} < 8$ MeV in region M, and from the efficiency of this selection as determined for quasielastic events. The remainder was attributed to (γ, π^0) induced events. The shape of the $E\theta^2$ distribution for coherent π^0 production and for the different background processes was then calculated by Monte Carlo simulation. Extrapolation into the forward region yields for F + M together 383 (γ, π^0) events in the neutrino and 721 (γ, π^0) events in the antineutrino case. These numbers still contain events from background source 3. Their contribution is estimated by using regions B1 and B2. In these regions the observed events are attributed to electron-induced or γ -induced electromagnetic showers by making use of the appropriate E_{first} distributions. From that result we extrapolated the expected number of incoherent (γ, π^0) induced events into the regions F and M. The results are summarized in table 1.

TABLE 1

Number of events
with statistical and systematical errors

	$N_{\gamma\pi\text{raw}}$	N_{incoh}	$N_{\pi\text{coh}}$
ν	$383 \pm 31 \pm 22$	$160 \pm 65 \pm 48$	$223 \pm 53 \pm 72$
$\bar{\nu}$	$721 \pm 48 \pm 50$	$239 \pm 87 \pm 74$	$482 \pm 83 \pm 99$

In order to calculate the cross sections of the reactions $(\bar{\nu})_{\mu} A \rightarrow (\bar{\nu})_{\mu} A \pi^0$ the fluxes of the various types of neutrinos in the beam have to be determined. The ratio of ν_{μ} and $\bar{\nu}_{\mu}$ fluxes in the neutrino beam and of $\bar{\nu}_{\mu}$ and ν_{μ} fluxes in the antineutrino beam were experimentally determined from the observed numbers of elastic and quasielastic charged-current reactions associated with a μ^- and μ^+ [14], whilst the $\nu_e(\bar{\nu}_e)$ contaminations were computed using a Monte Carlo simulation program [13]. The following event rates due to these components were found:

$$\nu \text{ beam: } \nu_{\mu}: \bar{\nu}_{\mu}: \nu_e: \bar{\nu}_e = 1.00: 0.04: 0.009: 0.002$$

$$\bar{\nu} \text{ beam: } \bar{\nu}_{\mu}: \nu_{\mu}: \bar{\nu}_e: \nu_e = 1.00: 0.12: 0.008: 0.005$$

The total (anti)neutrino beam flux was monitored in two independent ways by recording the events induced by inclusive charged-current and neutral-current processes on nucleons [19], and the events induced by quasielastic $\nu_{\mu}(\bar{\nu}_{\mu})$ charged-current processes on nucleons [13]. Some of the systematic errors implicit in the normalization procedure were monitored by the time variation of the ratio between the two normalization factors during the three years of running. The observed r.m.s. variation is 4%.

From the measurements we evaluated the following visible cross sections for $6 \text{ GeV} < E_{\pi} < 20 \text{ GeV}$ and for $E_{\theta^2} < 100 \text{ MeV}$:

$$\nu_{\mu}: \sigma_{\text{vis}} = (18.1 \pm 6.0 \pm 5.1) \cdot 10^{-40} \text{ cm}^2 / \langle \text{nucleus in marble} \rangle \quad (2)$$

$$\bar{\nu}_{\mu}: \sigma_{\text{vis}} = (13.5 \pm 3.0 \pm 3.2) \cdot 10^{-40} \text{ cm}^2 / \langle \text{nucleus in marble} \rangle .$$

and the experimental value for their ratio

$$R = \sigma_{\text{vis}}(\nu_{\mu}) / \sigma_{\text{vis}}(\bar{\nu}_{\mu}) = 1.34 \pm 0.53 \quad (3)$$

Part of the systematic errors cancel in this ratio. Theoretically we expect this ratio to be equal to one; after correction for the different energy spectra of ν_μ and $\bar{\nu}_\mu$ we expect a value of 1.13 ± 0.04 .

We evaluated the efficiency of detecting a coherently produced π^0 for an average marble (CaCO_3) nucleus in the energy window from 6 to 20 GeV, using a Monte Carlo simulation according to the theory of Rein and Sehgal [3]. The difference between the spectra of the neutrino ($\langle E_\nu \rangle = 31$ GeV) and the antineutrino beam ($\langle E_{\bar{\nu}} \rangle = 24$ GeV), as determined by charged current events, was taken into account. We found for that model [3] the following efficiencies: $\varepsilon_{\text{vis}} = 0.21 \pm 0.01$ for the neutrino beam and $\varepsilon_{\text{vis}} = 0.19 \pm 0.01$ for the antineutrino beam. The efficiency for the requirement $E_{\pi^0} < 100$ MeV is $\varepsilon = 0.90 \pm 0.04$. The resulting visible and corrected experimental cross sections are given in table 2; their statistical and systematic errors were quadratically combined.

TABLE 2

Summary of visible and corrected experimental cross sections for coherent π^0 -production. The theoretical values were calculated following ref. [3]. All cross sections are given per average marble nucleus in units of 10^{-40} cm^2

	measured	corrected	theoretical
ν_μ	$\sigma_{\text{vis}} = 18.1 \pm 7.9$	$\sigma = 96 \pm 42$	$\sigma = 74 \pm 38$
$\bar{\nu}_\mu$	$\sigma_{\text{vis}} = 13.5 \pm 4.4$	$\sigma = 79 \pm 26$	$\sigma = 71 \pm 34$

The theoretical values in table 2 were evaluated according to ref. [3], assuming $\beta = 1$ and $\rho = 1$. Their errors are due to uncertainties in the nuclear radii. Comparing the experimental and theoretical values of table 2, averaged for neutrinos and antineutrinos, we determined the isovector neutral current coupling constant and found

$$|\beta| = |u_a - d_a| = 1.08 \pm 0.24 \quad (4)$$

assuming $\rho = 1$. Statistical error (0.10) and systematic error (0.21) are quadratically combined. Fig.4 shows our result together with the theoretical predictions and experimental results from previous experiments [4,18].

The uncertainties of the theoretical calculation can be partly eliminated by comparing the visible cross-section of coherent π^0 production (table 2) with that of coherent π^- production in the antineutrino induced charged-current reaction on neon which has recently been measured at CERN by a BEBC collaboration [18]. Assuming again $\rho = 1$ [10] we found

$$|\beta| = |u_a - d_a| = 1.10 \pm 0.23 \quad (5)$$

in agreement, within the errors, with the previous result obtained by comparing with the theoretical cross section. These results agree within the errors with the value of 1.0 predicted by the Standard model and hence with the relative sign $u_a = -d_a$ of the axialvector coupling constants of u and d quarks.

We would like to thank D. Rein for discussions of the theoretical aspects of coherent pion production by neutrinos. We are indebted to P. Marage from the WA59-collaboration for private communications on coherent π^- production induced by $\bar{\nu}_\mu$ charged-current interactions. We would like to express our gratitude and appreciation to our numerous technical collaborators. The successful realization of the detector was only possible thanks to their skill and dedication. We acknowledge the contributions of A.N. Diddens, E. Lillethun and A.M. Wetherell to this experiment.

REFERENCES

1. O.Nachtmann, Nucl.Phys. B22 (1970) p.385
2. K.S.Lackner, Nucl.Phys. B153 (1979) p.526 and Doctoral Thesis, Heidelberg 1978, unpublished
3. D.Rein und L.M.Sehgal, Nucl.Phys. B223 (1983) p.29
4. H.Faissner et al., Phys.Lett. 125B (1983) p.230
5. E.Isiksal, D.Rein und J.G.Morfin, Phys.Rev.Lett. 52 (1984) p.1096
6. P.Marage et al., Phys.Lett. 140B (1984) p.137
7. M.Jonker et al., CHARM-Coll., Phys.Lett. 105B (1981) p.185
8. F.Bergsma et al., CHARM-Coll., Phys.Lett. 117B (1982) p.272
9. F.Bergsma et al., Phys. Lett. 147B (1984) p. 481
10. see e.g. J.Panman, Electroweak Neutral-Current Interactions, Rapporteurs talk at Neutrino '84 Int. Conf., Dortmund
11. P.Q.Hung and J.J.Sakurai, Ann. Rev. Part. Sci. 31 (1981) p. 375
12. A.N.Diddens et al., CHARM-Coll., Nucl.Inst.and Meth. 178(1980)27
13. C.Visser, NUBEAM, CERN HYDRA-application library write-up (1979)
14. M.Jonker et al., CHARM-Coll., Phys.Lett. 93B (1980) p.203 and Phys.Lett. 122B (1983) p.185
15. M.Jonker et al., Nucl. Inst. and Meth. 215 (1983) p. 361
16. J.Asplazu, Diplomarbeit 1981, II.Inst.Exp.Phys. Hamburg, unpublished
17. R.L.Ford und W.R.Nelson, The EGS Code System, report SLAC-210/UC-32 (1978)

18. P.Marage, WA-59 Coll., Doctoral Thesis, Bruxelles 1984, unpublished
19. M.Jonker et al., CHARM-Coll., Phys.Lett. 99B (1981) p.265

FIGURE CAPTIONS

1. Separation of electron and pion induced showers using the scintillator- (Γ) and proportional drifttube- (Δ) dependent estimators respectively at 15 GeV test beam energy.
2. $E\theta^2$ distribution of events passing the selection criteria. The boundaries of the regions used to evaluate the background are marked.
 - (a) Neutrino beam,
 - (b) Antineutrino beam.
3. Energy observed in the first scintillator plane after the vertex (E_{first}) for
 - (a) quasielastic ν_e ($\bar{\nu}_e$) induced events,
 - (b) coherent π^0 s as simulated by the EGS Monte Carlo program.
4. Cross sections for coherent π^0 production as a function of neutrino energy showing a comparison of the experimental data with theoretical models. The horizontal error-bars indicate the range of neutrino-energies used for the particular points. For the CHARM results 68% of the events have a neutrino energy within the errorbars.

Fig.1

Fig. 2

Fig.3

Fig. 4