1 July 1981

81-7-287
高工研圖書室

MEASUREMENT OF THE CROSS SECTION OF ANTINEUTRINO
SCATTERING ON ELECTRONS

The CHARM Collaboration

M. Jonker, J. Panman and F. Udo

NIKHEF, Amsterdam, The Netherlands

J.V. Allaby, U. Amaldi, G. Barbiellini¹, W. Flegel,
W. Kozanecki², K.H. Mess, M. Metcalf, J. Meyer³,
P. Monacelli⁴, R.S. Orr⁵, A.M. Wetherell and K. Winter
CERN, Geneva, Switzerland

V. Blobel, F.W. Büsser, P.D. Gall, H. Grote, B. Kröger³,
E. Metz, F. Niebergall, K.H. Ranitzsch and P. Stähelin

II. Institut für Experimentalphysik*, Universität Hamburg, Hamburg, Germany

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

A. Baroncelli⁶, R. Biancastelli⁶, B. Borgia⁷, C. Bosio⁶, A. Capone⁷,
F. Ferroni⁷, E. Longo⁷, F. de Notaristefani⁷, P. Pistilli⁷,
C. Santoni⁶ and V. Valente⁸

Istituto Nazionale di Fisica Nucleare, Rome, Italy

(Submitted to Physics Letters)

¹ On leave of absence from INFN, LN Frascati, Italy

² Now at University of California, Riverside, California, U.S.A.

³ Now at DESY, Hamburg, Germany

⁴ On leave of absence from Istituto di Fisica, Università di Roma and INFN
Sez. di Roma

⁵ Now at University of Toronto, Toronto, Ontario, Canada

⁶ INFN Sez. Sanità and Istituto Superiore di Sanità, Roma

⁷ Istituto di Fisica, Università di Roma and INFN Sez. di Roma

⁸ Laboratori Nazionali INFN Frascati, Italy

* Supported by Bundesministerium für Forschung und Technologie, Bonn,
German Federal Republic

ABSTRACT

A sample of 1,450,000 interactions with shower energy larger than 2/GeV has been observed in a fine grain calorimeter exposed to the CERN SPS wide-band antineutrino beam. Among these, 72 ± 16 events can be attributed to the neutrino-electron interaction and lead to a value of $\sin^2 \theta = 0.29 \pm 0.05$ (stat) corresponding to a cross-section for the reaction $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ of $(1.70 \pm 0.33) \times 10^{-42} E_\nu$ (cm²/GeV). The systematic error, due to the uncertainties in the knowledge of the antineutrino spectrum, of the electron detection efficiency and of the antineutrino nucleon total cross-section, is estimated to be $\pm 25\%$.

The first experimental observation of a weak neutral-current phenomenon was on the scattering of $\bar{\nu}_\mu$ on electrons¹⁾. Further observations, in particular on semileptonic neutral current neutrino reactions^{2,3)}, have by now lent strong support to a unified gauge theory of weak and electromagnetic interactions, as proposed by Glashow, Salam and Weinberg.

The main goal of pursuing the study of neutrino and antineutrino scattering on electrons is to determine the coupling constants of the leptonic weak neutral current and to compare them with the predictions of the gauge model, thus avoiding the ambiguities inherent in the use of hadronic targets. Until now, however, the extremely low cross-section of the reaction

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \quad (1)$$

has drastically limited the number of observed events³⁾, as illustrated in Table 1. At high energy the bubble-chamber data show an anomalously low number of candidates: instead of six events expected according to the standard model, only one has been found⁴⁾.

TABLE 1

Summary of $\bar{\nu}_\mu e^-$ scattering results

Experiment	Ref.	CC sample	$\bar{\nu}_\mu e^-$ cand.	Background	σ/E_ν (10^{-42} cm ² /GeV)
GGM (PS)	3a		3	0.4 ± 0.1	$1.0^{+2.1}_{-0.9}$
Aachen- Padova (PS)	3b		8	1.7	2.2 ± 1.0
GGM (SPS)	3e	7400	0	< 0.2	< 2.7 (90% c.l.)
FMMS FNAL 15'	3f	8400	0	0.2 ± 0.2	< 2.1 (90% c.l.)
BEBC TST (SPS)	3g	7500	1	0.5 ± 0.15	< 3.4 (90% c.l.)

In the present experiment, use was made of a fine-grain calorimeter in an attempt to combine the advantages of bubble chambers in identifying the events due to antineutrino scattering on electrons and of massive calorimeters in obtaining higher event rates.

The experiment was performed in the horn-focused wide-band antineutrino beam of the CERN 400 GeV Proton Synchrotron (SPS). Data were collected for $\sim 4.3 \times 10^{18}$ protons of 400 GeV on target. In this beam the antineutrino spectrum extended from a few GeV to beyond 100 GeV with an average energy of 24 GeV. The beam contains different neutrino components with the following energy-weighted ratio:

$$\bar{\nu}_\mu : \nu_\mu : \bar{\nu}_e : \nu_e = 1.00 : 0.09 : 0.01 : 0.005.$$

The cross-section for antineutrino-electron scattering is expected to be between three and four orders of magnitude smaller than the antineutrino nucleon cross-section at the same laboratory neutrino energy. The single scattered electron has to be identified by making use of the distinctive characteristics of the kinematics of reaction (1) compared with those of semileptonic processes. For high incident energies, the electron recoils at very small angles [$< (2m_e c^2/E)^{1/2} \approx 7$ mrad] with respect to the antineutrino direction which is known to within 1 mrad. The electron direction was determined by measuring the spatial distribution of the energy deposition of the electromagnetic shower in the material of the calorimeter, consisting mostly of marble, of average density $\langle \rho \rangle \approx 1.3$ g/cm³ and average atomic number $\langle Z \rangle \approx 13$.

A detailed description of the apparatus is given elsewhere⁵⁾. Here only the main features of the detector are recalled. The target calorimeter consists of 78 subunits. A subunit comprises a marble plate of 3×3 m² surface area and 8 cm thickness, followed by two planes of sensitive elements: i) 128 proportional drift tubes, each tube having dimensions of $3 \times 3 \times 400$ cm³, and ii) 20 plastic scintillators of dimensions $15 \times 3 \times 300$ cm³, oriented at 90° with respect to the tubes. A subunit is one radiation length thick. The target calorimeter is followed by four toroidal iron magnets each containing 75 cm of iron to detect muons produced in charged current events. A partial schematic view of the apparatus is shown in Ref. 5). The apparatus measures the angle and the energy deposited by an electromagnetic shower with the resolutions given in Table 2.

TABLE 2

Energy and projected angle r.m.s. resolution for electromagnetic showers

Electron energy (GeV)		15	20	50
Energy resolution (%)		5.0	4.5	2.8
Resolution of projected angles in mrad (r.m.s.)	$\Delta\theta_1$ a)	10	10	6
	$\Delta\theta_2$ a)	14	12	8

a) θ_1 is the angle in the projection in which the vertex is defined by a single tube hit (see text), θ_2 is the angle in the other projection.

The present data sample corresponds to 1,450,000 interactions observed in the antineutrino beam with shower energies larger than 2 GeV, produced in a fiducial volume of $2.3 \times 2.3 \text{ m}^2$ in area and 60 subunits long. The fiducial mass is 80 tons. To select antineutrino electron scattering events we have searched for those with showers which: i) occur at small angles with respect to the neutrino beam, and ii) are recognized as being of electromagnetic nature. In the analysis, these tasks were performed by the two sets of sensitive elements, the proportional drift tubes and the scintillators. The shower angle measured by the proportional tubes^{5,6)} is determined in each projection by the line joining the shower vertex to the shower centre. Only events with a single hit in the first tube plane of the shower have been used in the analysis. The measured drift time in the hit tube determines the vertex position in this projection except for a left-right ambiguity. This ambiguity has been resolved with the help of a visual scan when the drift distance exceeded 4 mm. As events with a single hit in the second tube plane were rare, the centre of gravity of the energy deposited in the tubes was used for the determination of the vertex in the corresponding projection. The calculation of the shower centre made use of the energy deposited in the proportional tubes and gave a weight to the lateral profile which decreased with the distance from the shower axis. The angular resolutions $\Delta\theta_{1,2}$, thus achieved, are slightly energy dependent and are determined by the error in the location of the vertex and by fluctuations in the position of the centre of the shower. Calibration measurements have been performed in an electron beam at energies of 15, 20 and 50 GeV⁵⁾. The resulting resolutions are given in Table 2.

The very narrow angular distribution of recoil electrons in the reaction $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ is broadened by the finite resolution of the calorimeter. The measured angles are expected to lie within an energy-dependent solid angle of $\approx \{\Delta\theta_1^2 + \Delta\theta_2^2\}$ centred around the $\bar{\nu}$ -direction. To limit this energy dependence, the raw data were limited to the 990,000 events with shower energy larger than 7.5 GeV. The hadron energy distribution for these events agrees very well with the expected distribution computed using the CERN wide-band beam Monte Carlo program⁷⁾, and the appropriate y -distribution.

In order to select, from this large sample, the small number of single electrons due to antineutrino-electron scattering, the following criteria were applied.

- A) Charged current semileptonic events were rejected by the requirement that no single track longer than eight radiation lengths (i.e. two interaction lengths) was found by the pattern recognition subroutine.
- B) Events were rejected if the shower direction deviated by more than 100 mrad from the direction of the incoming antineutrino beam. Since all antineutrino-electron scattering events occur at nearly forward direction in the laboratory frame, no good events were lost in this step.
- C) The most effective criterion, allowing a reduction of the data sample by a factor of about 50, was based on the different widths of electromagnetic and hadronic showers. The lateral shower profile, as measured in the vertical and horizontal plane by the scintillators, was used to calculate the width Γ of a Cauchy distribution fitted to the central part of the shower. A second parameter, σ , was determined by the r.m.s. width of the shower profiles as measured in a larger fiducial area by the proportional tubes. While Γ parametrizes the width of the shower core, σ is sensitive to the tails of the shower profiles. Figure 1 shows the distributions of the width parameters Γ and σ obtained in a test beam of pions and electrons of 20 GeV. Events were selected if $\Gamma < 1.6$ cm and $\sigma < 9$ cm. The resulting efficiency for the acceptance of electrons is $\epsilon_C = (85 \pm 5)\%$, while the rejection of showers induced by incident charged pions is better than 99%. The test beam data show that this efficiency is energy independent in the selected energy range.

- D) Most of the hadronic events remaining in the sample were rejected by requiring:
- i) a single hit in the first tube plane. This removes the scintillator material from the fiducial mass reducing it to 71 tons;
 - ii) energy deposition in the first scintillator plane following the vertex not exceeding the energy deposited by seven minimum ionizing particles.

Measurements in the test beam gave $\epsilon_D = (71 \pm 10)\%$ for electrons and, taking into account small correlations, a combined efficiency of criteria C) and D) of $\epsilon_{CD} = (61 \pm 9)\%$ for electrons and $\epsilon_{CD} < 0.2\%$ for pions.

In the range of shower energy $7.5 < E < 30$ GeV, where we expect the best signal-to-background ratio, we observe a sample of 537 events with $E^2\theta^2 < 0.54$ GeV². The upper energy cut, also used in a previous experiment^{3b)}, is applied to eliminate high-energy events due to elastic and quasi-elastic charged current reactions induced by the $\bar{\nu}_e^{(-)}$ component of the beam. In these events the electron energy is relatively large because it is almost equal to the $\bar{\nu}_e^{(-)}$ energy. Moreover, the angular distribution of the events with energy greater than 30 GeV is such that a large fraction of them has an angle smaller than the experimental resolution.

The 537 selected events are plotted versus the variable $E^2\theta^2$ in Fig. 2a. These events include the signal of single electrons from elastic antineutrino electron scattering, but also electromagnetic showers from the following background processes:

- a) elastic and quasi-elastic charged current events induced by the ν_e and $\bar{\nu}_e$ components of the beam;
- b) semileptonic neutral current events with a dominant electromagnetic component.

Because of the finite angular resolution of the calorimeter, the signal events are distributed in a range of $E^2\theta^2$ larger than the region allowed by the kinematics of $\bar{\nu}_\mu^{(-)}$ scattering ($E^2\theta^2 < 2m_e c^2 E < 0.03$ GeV²). The measured angular resolution implies that 90% of these events have $E^2\theta^2$ values less than 0.12 GeV², corresponding to the first two bins of Fig. 2a.

The $E^2\theta^2$ distribution of background a) has been experimentally determined by using data on elastic and quasi-elastic charged current reactions induced by muon antineutrinos:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \quad , \quad (2)$$

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X \quad , \text{ with } E_x < 0.5 \text{ GeV} \quad (3)$$

At energies larger than 7.5 GeV, the cross-sections of these reactions are known to be energy independent functions of the transverse momentum $P_T = E^2\theta^2$. The same functions also describe the $E^2\theta^2$ distributions of the elastic and quasi-elastic reactions for the $\bar{\nu}_e$ and ν_e components of the beam [background a)]. Figure 3 shows the observed $E^2\theta^2$ dependence of $\bar{\nu}_\mu$ induced events with $E_\mu > 7.5$ GeV and with $E_h < 0.5$ GeV ⁸⁾. The events of Fig. 3 have been folded with the measured electron angular resolution (Table 2). The continuous line represents a fit to the measured events as discussed in Ref. 8.

The $E^2\theta^2$ dependence of background b) was determined by Monte Carlo simulation based on the antineutrino energy spectrum, the neutral current q^2 dependence and the experimental resolutions. The normalization of backgrounds a) and b) was obtained by a study of the energy deposition in the first scintillator plane following the shower vertex for different regions of the variable $E^2\theta^2$. This study has also shown that the observed $E^2\theta^2$ distributions of the semileptonic neutral current events agree with the shape computed in the Monte Carlo simulation. This analysis is based on the observation that the events with an electromagnetic shower initiated by a π^0 produced by semileptonic neutral current processes have an energy deposition in this scintillator corresponding mainly to an even number of minimum ionizing particles (MIP). However, the events due to $\bar{\nu}_\mu$ -electron scattering and to background a) give an energy deposition corresponding mainly to an odd number of MIPs, as expected for one electron or one electron plus a converted bremsstrahlung photon. Figures 4a and 4b show the energy deposition in the first scintillator with peaks at 1, 2, 3 MIPs, and indicate that at large values of $E^2\theta^2$ background b) gives the larger contribution.

The continuous line in Fig. 2a represents the result of a best fit to the data, assuming that the background originates wholly from sources a) and b). The result of the fit attributes ~ 175 events to background a). The semileptonic neutral-current component accounts for ~ 282 events and is compatible with the assumption of a large contribution from coherent π^0 production as predicted by Lackner⁹⁾.

The extrapolated background in the region $E^2\theta^2 < 0.12 \text{ GeV}^2$ is 131 events. After subtraction, the number of events is (72 ± 16) events with a total efficiency $\epsilon_{\text{tot}} = \epsilon_{\text{CD}} \times \epsilon(E^2\theta^2 < 0.12 \text{ GeV}^2) = (55 \pm 8)\%$. Most of these events have a single electron (or positron) produced at an angle smaller than the angular resolution in space ($\Delta\theta < 1^\circ$). This interpretation is supported by the measurement of the energy loss in the scintillator following the marble plate in which the interaction took place (see Fig. 4.) Of the events plotted in Fig. 2a those with an energy loss corresponding to less than 1.5 minimum ionizing particles (i.e. $< 9 \text{ MeV}$) have the $E^2\theta^2$ distribution shown in Fig. 2b. The signal is reduced by a factor ~ 3 but the background by a factor of almost 10. Among the events with $E^2\theta^2 < 0.12 \text{ GeV}^2$, 25 ± 7 events are attributed to antineutrino-electron scattering; this number is consistent with the 72 candidates found in the full sample and a measured efficiency of $\sim 35\%$ for observing electromagnetic showers initiated by single electrons which deposit energy less than 1.5 minimum ionizing particles after one-half radiation length of marble.

In order to calculate the cross-section for $\bar{\nu}_\mu e$ scattering one has to know the flux of the various types of neutrinos in the beam. The ratio $\bar{\nu}_\mu/\nu_\mu$ was experimentally determined from the observed μ^+/μ^- ratio, while the $\bar{\nu}_e$ fluxes were computed using the CERN wide-band beam Monte Carlo program⁷⁾. The ratio of the number of expected events in the visible energy range 7.5-30 GeV for the four processes of neutrino-electron scattering that contribute to the observed peak is:

$$\bar{\nu}_\mu : \nu_\mu : \bar{\nu}_e : \nu_e = 1.00 : 0.09 : 0.03 : 0.02.$$

In computing these ratios a value of $\sin^2\theta = 1/4$ has been assumed for the weak mixing angle. Thus, the 72 events observed are attributed to the various reactions on electron targets in the following way:

$$\bar{\nu}_\mu : \nu_\mu : \bar{\nu}_e : \nu_e = 63 : 6 : 2 : 1.$$

The normalization to the number of incoming antineutrinos was done by making use of the known¹⁰⁾ antineutrino-nucleon total cross-section $[0.41 E_\nu \cdot 10^{-38} \text{ (cm}^2\text{/GeV)}]$ and by measuring the number of antineutrino (and neutrino) interactions in the same fiducial volume of the calorimeter. Because of the energy acceptance $7.5 < E < 30 \text{ GeV}$, the y -distribution of $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ must be known to derive the total cross-section. In the Glashow-Salam-Weinberg model the y -distribution depends on $\sin^2\theta$. The observed number of events agrees with the prediction of the GSW model for

$$\sin^2\theta = 0.29 \pm 0.05 \text{ (stat)} \quad (4)$$

The corresponding cross section is¹³⁾

$$\sigma_{\bar{\nu}_\mu e}^- / E_\nu^- = (1.70 \pm 0.33) \cdot 10^{-42} \text{ cm}^2\text{/GeV} \quad (5)$$

Three main sources of systematic errors have been considered: the background shape ($\pm 20\%$), the electron detection efficiency ($\pm 15\%$) and the normalization to the total antineutrino nucleon cross-section at the typical energy of the wide-band neutrino beam ($\pm 6\%$). The three systematic errors are quadratically combined to give a total systematic error of $\pm 25\%$

The present result agrees, within the still large statistical and systematic errors, with what has been found in previous experiments on purely leptonic weak interactions¹¹⁾. The value of $\sin^2\theta$ deduced from the data confirms that the weak neutral current in neutrino-lepton interactions has the same strength as in neutrino quark interactions^{10,12)}.

We would like to express our gratitude and deep appreciation to our numerous technical collaborators. The successful realization of the detector was only possible thanks to their skill and dedication. In particular, we wish to thank W. Albrecht, G. Basti, C. Busi, Dr F. Cesaroni, R. Donnet, M. Ferrat, B. Friend, V. Gemanov, S. Guerra, E. Gygi, M. Jimenez, A. King, Dr L. Luminari, G. Lunadei, Y. Perrin, Dr G. Petrucci, G. Pozzo, Dr F. Schneider, J. Schütt, L. Sokolov, J.C. Tarlé, A. Tusi, P. Veneroni, H. Verweij and the SPS staff for the operation of the accelerator. We wish to express our gratitude to Dr A.N. Diddens for his contribution to this experiment.

REFERENCES AND NOTES

- 1) F.J. Hasert et al., Phys. Lett. 46B (1973) 121.
- 2) See, for example:
U. Amaldi, Rapporteur's talk, Proc. Neutrino '79, Bergen, 1979 (Univ. Bergen, 1979) vol. 1, p. 367;
F. Dydak, Rapporteur talk at the 1979 EPS Int. Conf. on High Energy Physics, Geneva, 1979 (CERN, Geneva, 1980) vol.1, p.25;
B. Borgia, Rapporteur's talk at the 1980 Neutrino Conference, Erice (unpublished);
F. Sciulli, Rapporteur's talk, Proc. 20th Int. Conf. on High Energy Physics, Madison, 1980 (eds L. Durand and Lee G. Pondrom) (American Inst. Phys., New York, 1981) Part 2, p. 1279.
- 3) a) J. Blietschau et al, Nucl. Phys. B114 (1976) 189.
b) H. Faissner et al., Phys. Rev. Lett. 41 (1978) 213.
c) P. Alibrand et al., Phys. Lett. 74B (1978) 422.
d) A.M. Cnops et al., Phys. Rev. Lett. 41 (1978) 357.
e) D. Bertrand et al., PITHA preprint 79/07 (1979).
f) J.P. Berge et al., FNAL preprint 79/27 EXP. (1979).
g) N. Armenise et al., BEBC-TST Collaboration, Phys. Lett. 81B (1979) 385
h) M. Jonker et al., CHARM Collaboration, Proc. Neutrino '79, Bergen vol. I. p, 219.
- 4) See, for example:
F.W. Bullock, Rapporteur's talk Proc. Neutrino '79, Bergen, vol. 1, p.398;
K. Winter, Rapporteur's talk, Proc. 9th Int. Symp. on Lepton and Photon Interactions at High Energy, Batavia, 1979 (FNAL, Batavia, 1979), p.258.
- 5) A.N. Diddens et al., CHARM Collaboration, Nucl. Instrum. Methods 178 (1980) 27.
- 6) C. Bosio et al., CHARM Collaboration, Nucl. Instrum. Methods 157 (1978) 35.
- 7) C. Visser, NUBEAM CERN Hydra Application Library (1979).
- 8) M. Jonker et al., CHARM Collaboration, Phys. Lett. 93B (1980) 203.
- 9) K. Lackner, Nucl. Phys. B153 (1979) 526.
- 10) M. Jonker et al., CHARM Collaboration, Phys. Lett. 99B (1981) 265.
- 11) F. Reines et al., Phys. Rev. Lett. 37 (1976) 315;
R.H. Hersterberg et al., Phys. Rev. Lett. 44 (1980) 635;
W. Bartel et al., JADE Collaboration, Phys. Lett. 92B (1980) 206;
D.P. Barber et al., MARK J Collaboration, Phys. Lett. 95B (1980) 149;
R. Brandelik et al., TASSO Collaboration, Phys. Lett. 94B (1980) 259;
- 12) J.E. Kim et al., Rev. Mod. Phys. 53 (1981) 211.
- 13) The correlation between the energy acceptance and $\sin^2\theta$ is such that the relative error on the total cross-section is slightly smaller than the error on the observed rate.

FIGURE CAPTIONS

- Fig. 1 : Distributions of the width of 20 GeV electron and pion showers, a) as measured by the scintillators and b) as measured by the proportional tubes. The width parameters Γ and σ are discussed in the text.
- Fig. 2 : Distributions of the candidate events versus the variable $E^2\theta^2$.
a) Events satisfying the selection criteria discussed in the text.
b) Subset of sample a) satisfying the criterion that the energy deposition in the first scintillator plane of the shower is $E_F < 9$ MeV, corresponding to less than 1.5 minimum ionizing particles. This selection favours electrons produced in the latter half of the marble plate which are measured with better resolution.
- Fig. 3 : $E^2\theta^2$ distribution of the events $\nu_\mu^- + N \rightarrow \mu^+ + X$ with an energy transfer $E_x < 0.5$ GeV, folded with the electron angular resolution. The full line represents the result of a fit.
- Fig. 4 : Distribution of the energy E_F deposited in the first scintillator plane of the shower. The arrows indicate the energy deposited by 1.5 minimum ionizing particles.
a) Events of Fig. 2a with $E^2\theta^2 < 0.12$ GeV². The ratio of the number of events below and above 9 MeV is $45/158 = 0.285 \pm .045$.
b) Events with $E^2\theta^2 > 0.12$ GeV². The ratio of the number of events below and above 9 MeV is $44/290 = 0.152 \pm 0.025$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4