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**A NEW MEASUREMENT OF THE CROSS SECTION OF THE
INVERSE MUON DECAY REACTION $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$**

The CHARM II Collaboration

D. Geiregat¹ and G. Wilquet²

Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

U. Binder, H. Burkard, U. Dore³, W. Flegel, H. Grote, T. Mouthuy, H. Øveras,
J. Panman, R. Santacesaria⁴, P. Vilain^{2,5}, K. Winter, G. Zacek and V. Zacek
CERN, Geneva, Switzerland

R. Beyer, F.W. Büsser, C. Foos, L. Gerland, T. Layda,
F. Niebergall, G. Rädcl, P. Stähelin and T. Voss

**II. Institut für Experimentalphysik⁶, Universität Hamburg, Hamburg,
Federal Republic of Germany**

D. Favart, G. Gregoire and E. Knoops¹

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Gorbunov, E. Grigoriev, V. Khovansky, A. Maslennikov and A. Rozanov⁷
Institute for Theoretical and Experimental Physics, Moscow, USSR

W. Lippich, A. Nathaniel, H. Neumeyer and A. Staude

Sektion Physik der Universität⁶ München, Munich, Federal Republic of Germany

M. Caria⁸, B. Eckart, A. Ereditato, R. Iasevoli, V. Palladino and P. Strolin
Università e Istituto Nazionale di Fisica Nucleare (INFN), Naples, Italy

A. Capone⁹, D. De Pedis, E. Di Capua¹⁰, A. Frenkel-Rambaldi,
P.F. Loverre, G. Piredda and D. Zanello

Università 'La Sapienza' e Istituto Nazionale di Fisica Nucleare (INFN), Rome, Italy

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 - 4 On leave of absence from INFN, Rome, Italy
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 - 7 Now at CERN, Geneva, Switzerland
 - 8 Dipartimento di Scienze Fisiche, Università di Cagliari, Italy
 - 9 Facoltà di Scienze, Università di Potenza, Italy
 - 10 Dipartimento di Fisica, Università di Ferrara, Italy

Abstract

We have measured the cross section for inverse muon decay in the CERN neutrino wide band beam. From 4808 events observed in the CHARM II detector we derived for the Born term of the asymptotic cross section slope the result $[18.16 \pm 1.36] \cdot 10^{-42} \text{cm}^2 \text{GeV}^{-1}$. This cross section is in good agreement with the Standard Model prediction and allows to constrain the scalar coupling of the electron and muon to their neutrinos to $|g_{LL}^S|^2 < 0.405$ at 90% C.L.

1. Introduction

The most general description of the charged current weak interaction between leptons by a local, derivative free, lepton number conserving four-fermion interaction Hamiltonian contains 10 complex coupling constants [1]. Muon decay experiments determine 8 of these to be close to zero but cannot measure the remaining 2 constants individually. Expressed in the helicity projection form, the results from the muon decay experiments show that the interaction contains only the coupling constants g_{LL}^S and g_{LL}^V [2], which are constrained to $1/4 |g_{LL}^S|^2 + |g_{LL}^V|^2 \leq 1$. S stands for scalar and V for vector interaction and L for the left-handedness of muon and electron. The coupling g_{LL}^S requires right-handed neutrinos and g_{LL}^V left-handed ones. In the inverse muon decay (IMD) reaction, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$, the incoming neutrino is known to be left-handed. The measurement of the cross section, hence, determines $|g_{LL}^V|$ and allows, together with the information from muon decay, implying that all other coupling constants except g_{LL}^S and g_{LL}^V are negligible, to derive an upper limit on $|g_{LL}^S|$. In the Standard Model all coupling constants are predicted to be zero except $g_{LL}^V = 1$, and the cross section for IMD is predicted as

$$\sigma = \frac{G_F^2}{\pi} \cdot 2m_e E_\nu \left(1 - \frac{m_\mu^2}{2m_e E_\nu}\right)^2 = \sigma_{as} E_\nu \left(1 - \frac{m_\mu^2}{2m_e E_\nu}\right)^2,$$

where σ_{as} is usually called the asymptotic cross section slope.

The Standard Model cross section, weighted with the ν spectrum of the CERN wide band beam, is $167 \cdot 10^{-42} \text{ cm}^2$, more than 1000 times smaller than the total cross section on nucleons. To isolate this rare process we exploited its specific kinematical features. IMD events are characterized by a single outgoing muon without any visible recoil particle. The transverse momentum of the muon is kinematically constrained to $p_\perp^2 \leq 2E_\mu m_e$. The minimum energy of the muon is 10.9 GeV because of the energy threshold of the reaction.

2. Experimental procedure

The results presented in this letter were obtained using the CHARM II detector in the CERN neutrino beam. Detector and beam are described elsewhere [3]; here we summarize the features important for the study of IMD. The average energies of the wide band ν and $\bar{\nu}$ beams are $\langle E_\nu \rangle = 23.8 \text{ GeV}$ and $\langle E_{\bar{\nu}} \rangle = 19.3 \text{ GeV}$, respectively. The detector consists of an isoscalar target calorimeter of 531 t fiducial mass and a muon spectrometer. The target material is glass, stacked in 420 plates, each 1/2 radiation length thick, interspersed with streamer tube planes. The angular resolution for muons in the calorimeter is $18 \text{ mrad}/(E/\text{GeV})^{0.75}$ and the momentum resolution of the muon spectrometer is $\approx 15\%$ (averaged over the IMD events). The calorimetric measurement of hadronic energy has a resolution of $\sigma/E = 46\%/\sqrt{E/\text{GeV}}$.

Trigger and event selection for IMD required a muon in the spectrometer and not more than 10 clusters of consecutive wire hits additional to the muon track in the first 10 streamer tube planes after the vertex. This activity limit corresponds to 1.5 GeV hadronic energy. The acceptance and reconstruction efficiency has been calculated using Monte Carlo techniques and amounts to $(88.8 \pm 0.8)\%$. To determine the absolute ν flux we have used quasi-inclusive ν events, satisfying a threshold $E_{\text{had}} \geq 3$ GeV, which were recorded using a minimum bias trigger. The event sample for this analysis was obtained in 109 days of data taking and represents 1/3 of the total data taken until now. The analysis of the total sample is in progress.

3. Determination of the IMD signal

The $p_{\perp}^2$ distribution for events with low vertex activity and E_{μ} above IMD threshold is shown in fig. 1. For the ν beam, a clear signal of IMD is seen on a broad continuum of quasielastic-like events (charged current events on nuclei) which we call the background. For the $\bar{\nu}$ beam, where IMD is absent, the effect of the Pauli exclusion principle for small $p_{\perp}^2$ is visible.

Since no precise information on the Pauli exclusion effect for quasielastic scattering and on collective nuclear effects for ν -production of resonances is available [4, 5], the background shape cannot be reliably predicted. However, on general grounds, the backgrounds should be equal for ν and $\bar{\nu}$ reactions at $p_{\perp}^2 = 0$. The Adler theorem [6] states that for $Q^2 = 0$ (corresponding to $p_{\perp}^2 = 0$), ν and $\bar{\nu}$ have only axial vector interaction and, neglecting strangeness and charm production, interact equally. Under this assumption, for our isoscalar target the cross section is the same for neutrinos and antineutrinos. With increasing $p_{\perp}^2$ one expects (and sees in fig. 1) a slight difference due to a $V \cdot A$ interference term, which is approximately proportional to Q^2/E_{ν} [7], i.e. also to $p_{\perp}^2/E_{\nu}$. Our selection criterion of less than 10 clusters from hadronic activity is loose enough not to destroy the near equality of the background shapes. Applying a small correction for the $V \cdot A$ term, we used the $p_{\perp}^2$ distribution of $\bar{\nu}$ events for the background subtraction under the IMD peak. A harder cut would have improved the signal to background ratio, but would also have entailed an effective asymmetry of the backgrounds because of the larger charged particle multiplicity in ν events as compared to $\bar{\nu}$ events.

The near equality of the backgrounds is perturbed by strangeness producing quasielastic-like reactions, which are induced by antineutrinos only with a fraction of approximately $\sin^2\theta_C$ (Cabibbo mixing parameter) on free nucleons [8], and are expected not to be subjected to the Pauli exclusion effect. The asymmetry between the ν and $\bar{\nu}$ background introduced by these reactions is reduced by charm producing quasielastic-like reactions contributing to the ν background. The cross section for quasielastic charm production is not well known experimentally [9]. However, with the requirement $E_{\text{had}} < 1.5$ GeV it is reasonable to assume that charm production will not

overcompensate the asymmetry introduced by strangeness production. To take the possible effects from strangeness and charm production into account, we allowed the asymmetry to vary between 0, corresponding to equal contributions from strangeness and charm production, and its maximum value corresponding to only strangeness production with a fraction of $\sin^2\Theta_C$. As the central value we chose the mean between these two extremes. Technically this was achieved by constructing a $\bar{\nu}$ background distribution without the Pauli exclusion effect, and subtracting it with the corresponding weight from the observed $\bar{\nu}$ background.

The p_1^2 resolution, which varies with E_μ , and the $V \cdot A$ term both depend on E_ν . As the energy spectra for ν and $\bar{\nu}$ are slightly different we have split the data into five bins of E_μ . In each bin the average ν and $\bar{\nu}$ energy are equal to a very good approximation. The background subtraction has been performed for each bin separately. We have taken into account the effect of the $V \cdot A$ term in an approximate way. Outside the signal region the ratio of the backgrounds varies linearly with p_1^2 . This is illustrated in fig. 2a for events with muon energy above the IMD threshold. We have assumed that the linear behaviour persists under the signal peak. This is verified for events with a muon energy below the threshold [fig. 2b].

The IMD signal, combined for all energy bins after background subtraction, is shown in fig. 3. The shape, mainly determined by experimental resolution, agrees well with the Monte Carlo prediction. No events were found below the threshold and we take this as evidence for identifying the events above 10.9 GeV with IMD. We observe, after an 11.2% acceptance correction, $4808 \pm 192(\text{stat}) \pm 202(\text{syst})$ events. This number includes a 2.8% correction for the strangeness/charm production asymmetry. The systematic error is mainly due to the uncertainty of the background subtraction with the following contributions :

- 1.5% from the spread of estimated background values varying the p_1^2 range used for the linear extrapolation of the $V \cdot A$ term to $p_1^2 = 0$.
- 2.1% from a possible difference in the Pauli exclusion effect for ν and $\bar{\nu}$ events. The uncertainty arises from limits on the difference of the wave functions for protons and neutrons in light nuclei as in the target used in this experiment [10].
- 2.8% from the uncertainty of the strangeness/charm production asymmetry. This uncertainty is taken as large as the correction for the effect itself.

4. Cross section determination

The number of observed events is related to the asymptotic cross section slope σ_{as} by

$$N_{\text{IMD}} = \sigma_{as} \cdot N_e \cdot \int \frac{d\Phi}{dE_\nu} E_\nu \left(1 - \frac{m_\mu^2}{2m_e E_\nu}\right)^2 dE_\nu ;$$

N_e is the number of electrons in the target. The integral is the time integrated neutrino-flux Φ weighted with the energy dependence of the IMD cross section. We call this integral the flux integral.

We evaluated the flux integral from the number of observed inclusive NC and CC events and the shape of the ν -spectrum measured for quasielastic-like events. The error of the flux integral is composed of :

- 2.5% from the uncertainty of the total cross section for neutrinos on nuclei, which we obtained from a fit to existing data [11].
- 2.7% from the uncertainty of the loss of inclusive events due to the requirement $E_{\text{had}} \geq 3$ GeV.
- 0.4% from the uncertainty of contributions of $\bar{\nu}_\mu$ and ν_e to the inclusive events. The $\bar{\nu}_\mu$ abundance of the beam has been determined from quasielastic-like events with a positive muon, and the ν_e contamination was calculated by a beam simulation.
- 2.8% from the uncertainty of the ν -energy spectrum. This contribution arises because of the different energy dependence of the total ν -cross section and the IMD cross section.

Adding these errors in quadrature, we obtained for the flux integral $(1.71 \pm 0.08) \cdot 10^{12}$ GeV cm $^{-2}$; using $N_e = 1.60 \cdot 10^{32}$ we derived a cross section slope of

$$\sigma_{\text{as}} = [17.62 \pm 1.32] \cdot 10^{-42} \text{ cm}^2 \text{ GeV}^{-1} ,$$

where the error is quadratically combined of the statistical and systematic errors.

We have repeated the evaluation of σ_{as} for the five different muon energy bins described above. The asymptotic cross section slope as a function of the muon energy and the corresponding average neutrino energy is found to be constant within errors [fig. 4]. This is evidence that the energy dependence of the observed signal agrees with the theory.

5. Comparison with the Standard Model and limits on $|g_{\text{LL}}^{\text{S}}|^2$ and $|g_{\text{LL}}^{\text{V}}|^2$

For comparison with the Standard Model prediction, it is practical to deduce the Born term from the observed cross section by applying radiative corrections (which are experiment dependent). The radiative corrections have been calculated by Bardin and Dokuchaeva [12] and amount to 3% for this experiment. The corrected asymptotic cross section slope is then

$$\sigma_{\text{as}}^0 = [18.16 \pm 1.36] \cdot 10^{-42} \text{ cm}^2 \text{ GeV}^{-1} ,$$

in good agreement with the Born term of the Standard Model prediction ($17.23 \cdot 10^{-42}$ cm 2 GeV $^{-1}$) and with previous measurements [13,14]. Normalized to the Standard Model we obtained

$$S = \sigma_{\text{as}}^0 / 17.23 \cdot 10^{-42} \text{ cm}^2 \text{ GeV}^{-1} = 1.054 \pm 0.079.$$

As before, the left-handedness of the neutrinos in the beam and the constraints from muon decay ensure that only g_{LL}^V contributes to IMD and, therefore, $S = |g_{LL}^V|^2$. Using further the experimental constraint $1/4 |g_{LL}^S|^2 + |g_{LL}^V|^2 \leq 1$ from muon decay, we derived the limits

$$|g_{LL}^V|^2 > 0.899 \text{ at 90\% C.L. (0.942 at 68\% C.L.)}$$

$$|g_{LL}^S|^2 < 0.405 \text{ at 90\% C.L. (0.230 at 68\% C.L.)}$$

In the determination of these limits, we have used the method of [15] for deriving limits in the presence of a bounded physical region.

If we do not require the neutrinos to be left-handed, S depends also on g_{LL}^S : $S = |g_{LL}^V|^2 (1-\eta) + 1/12 |g_{LL}^S|^2 \eta$, where η is the fraction of right-handed neutrinos in the beam [16]. Limits (90% C.L.) are $\eta < 0.002$ for neutrinos from π -decay [2 and references therein] and $\eta < 0.044$ for neutrinos from K-decays [17]. Using this generalized expression for S together with the constraint $1/4 |g_{LL}^S|^2 + |g_{LL}^V|^2 \leq 1$, the limits for $|g_{LL}^S|^2$ and $|g_{LL}^V|^2$ become more strict for any value $\eta \neq 0$ allowed by experiments.

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Figure Captions

Figure 1

$p_{\perp}^2$ distribution for events with $E_{\mu} > 10.9$ GeV and $E_{\text{had}} < 1.5$ GeV for incident ν_{μ} (solid line) and $\bar{\nu}_{\mu}$ (marked with dots). The $\bar{\nu}_{\mu}$ -distribution was normalized to the ν_{μ} -distribution in the range $0.05 < p_{\perp}^2 < 0.1$ GeV²/c². The insertion shows the small $p_{\perp}^2$ region with the peak due to the inverse muon decay reaction.

Figure 2

Ratio of background events for incident ν and $\bar{\nu}$ vs, $p_{\perp}^2$ for E_{μ} above (a) and below (b) IMD- threshold. Above the threshold the point at 0.05 GeV²/c² is missing because it is hidden by the IMD-signal.

Figure 3

Distribution of inverse muon decay events as a function of $p_{\perp}^2$ after subtraction of the background. The solid line represents the expected distribution.

Figure 4

Observed asymptotic cross section of inverse muon decay as a function of the muon energy and corresponding average neutrino energy. The dashed line is the Standard Model prediction. Below threshold ($E_{\mu} < 10.9$ GeV) no signal is observed.

Fig. 1

Fig. 2

Fig. 3

Fig. 4