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A precise measurement of the cross section of the inverse muon decay $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

CHARM II Collaboration

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Abstract

We report our final results from the analysis of the full high statistics sample of events of the reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ collected with the CHARM II detector in the CERN wide-band neutrino beam during the years 1988 to 1991. From a signal of $15\,758 \pm 324$ inverse muon decay events we derived, in the Born approximation, a value of $(16.51 \pm 0.93) \times 10^{-42}\,\mathrm{cm}^2\,\mathrm{GeV}^{-1}$ for the asymptotic cross section slope σ/E_ν, in good agreement with the Standard Model prediction of $17.23 \times 10^{-42}\,\mathrm{cm}^2\,\mathrm{GeV}^{-1}$. The result constrains the scalar coupling of the electron and the muon to $|g_{LL}^S|^2 < 0.475$ at 90% CL.

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1. Introduction

The most general four-fermion interaction hamiltonian of the charged current weak interaction between leptons, assuming only locality and lepton number conservation, contains 10 complex coupling constants [1]. The helicity projection form of this hamiltonian, using fields of definite handedness, is the closest to a physical interpretation. Experiments on muon decay determine that at least one of the two couplings, the scalar coupling g^{S}_{LL} or the vector coupling g^{V}_{LL}, is nonzero. Both involve a left-handed muon and electron (LL). The remaining two couplings of the (RR) type and six couplings of the (LR) and (RL) type are found to be compatible with zero within tight bounds [2].

The scalar and vector coupling constants are constrained to

$$\tfrac{1}{4}|g^{S}_{LL}|^2 + |g^{V}_{LL}|^2 \leq 1 . \qquad (1)$$

As neutrino helicities are not determined in muon decay experiments they cannot discriminate between g^{V}_{LL}, i.e. left-handed ν_μ and right-handed $\bar{\nu}_e$, and g^{S}_{LL}, i.e. ν_μ and $\bar{\nu}_e$ of the opposite helicities. They thus cannot establish that the interaction is V–A, or equivalently that $g^{S}_{LL} = 0$ and $g^{V}_{LL} = 1$.

In the study of the inverse muon decay reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ (IMD) with a high energy neutrino beam, the incoming neutrino is known to be left-handed [3,4]. The only coupling involved is then g^{V}_{LL} and the cross section σ^0, in the Born approximation, is

$$\sigma^0 = \sigma^0_{as} E_\nu \left(1 - \frac{m_\mu^2}{s}\right)^2 |g^{V}_{LL}|^2 , \qquad (2)$$

with $s = 2m_e E_\nu$ and the so-called asymptotic cross section slope $\sigma^0_{as} = 2m_e G_F^2/\pi$. A measurement of the inverse muon decay cross section, hence, determines g^{V}_{LL} and, because of the relation (1), an upper limit on g^{S}_{LL}.

2. Signature of the IMD reaction

The IMD cross section is three orders of magnitude smaller than that of inclusive neutrino nucleon scattering. Unique features, however, distinguish the rare IMD events. They have a single outgoing muon without any visible recoil energy at the interaction point. The transverse momentum $p_\perp$ of the muon relative to the neutrino direction is kinematically constrained to $p_\perp^2 \leq 2m_e E_\mu$. The reaction can occur only above an energy threshold of

$$E_\nu \geq E_\mu \geq \frac{m_\mu^2}{2m_e} = 10.9\,\text{GeV} . \qquad (3)$$

3. Experimental set-up

The results we present here were obtained from data taken between 1988 and 1991 with the CHARM II detector exposed to the CERN wide-band neutrino and antineutrino beams. Detector and beam have been described in detail elsewhere [5,6]. Here we summarize only the features important for the study of the IMD.

The average energies of the neutrino and antineutrino beams are $\langle E_\nu \rangle = 23.8$ GeV and $\langle E_{\bar{\nu}} \rangle = 19.3$ GeV, respectively. The detector consists of two main parts: a target calorimeter and a muon spectrometer. The calorimeter contains 420 glass plates, each 0.5 radiation length thick, which are interspersed with streamer tubes and scintillator planes. It has a fiducial mass of 531 tons. The muon angle at the vertex is measured with a resolution of $18\,\text{mrad}/[E(\text{GeV})]^{0.75}$. The muon spectrometer consists of 6 toroidal magnets and 9 drift chambers with three wire planes each and achieves a momentum resolution of $\approx 15\%$ at 40 GeV, the average muon energy of IMD events.

The IMD events are selected from a data sample collected with the quasi-elastic neutrino nucleon scattering trigger. This trigger requires 1) a single muon produced in the calorimeter and penetrating into the muon spectrometer 2) low hadronic activity at the

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event vertex. The vertex activity after subtraction of the hits from the muon track is further restricted in the analysis to less than 11 clusters of hits in the first ten streamer tube planes of the event, where adjacent wire hits count as a cluster. According to the calibration in a pion beam this cut corresponds to a hadronic recoil energy of about 1.5 GeV. The acceptance for IMD under these conditions was calculated with a Monte Carlo simulation to be $(86.9 \pm 0.7)\%$.

The neutrino flux has been determined by counting all neutrino induced events and using the experimental value for the cross section of neutrino nucleon scattering [7]. This sample has been collected with a so-called minimum bias trigger, requiring only a minimum hadronic energy deposition of 3 GeV.

4. Extraction of the IMD signal

Fig. 1 shows the $p_\perp^2$ distributions for negative muons detected in the neutrino beam and for positive muons detected in the antineutrino beam, when requiring hadronic recoil energy less than 1.5 GeV and E_μ larger than 10.9 GeV. The distribution of events with μ^- taken in the neutrino exposures clearly exhibits a peak of IMD events at low $p_\perp^2$ above a broad continuum of charged-current neutrino nucleon scattering events with low hadronic activity, mostly of quasi-elastic nature. We will refer to this continuum as the background. The distribution of events with a μ^+ taken in the antineutrino exposures contains only background if one assumes additive lepton number conservation. Indeed, we see no IMD signal and therefore the suppression of the background due to the Pauli exclusion effect is observable down to $p_\perp^2 = 0$. The events in the μ^+ distribution have hadronic final states which are different from those of the background events in the μ^- distribution. The selection efficiency is however practically equal for both backgrounds, because of the large hadronic energy selection limit of 1.5 GeV.

No precise information on the Pauli exclusion effect for quasi-elastic scattering and on nuclear effects for neutrino induced production of resonances is available [8,9]; therefore the background shape cannot be reliably predicted. However, as discussed in more detail in our previous publication [10], the μ^+ distribution can be used to subtract the background under the

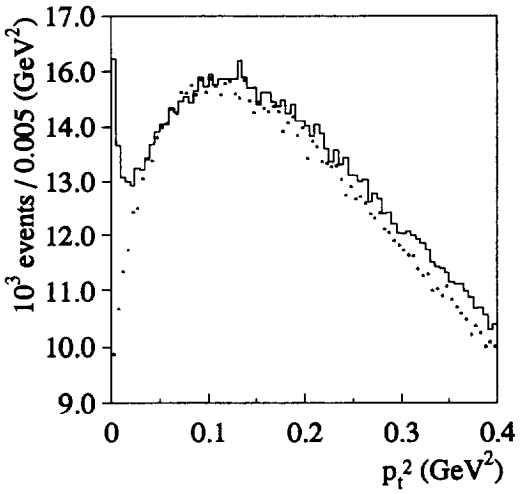

Fig. 1. $p_\perp^2$ distribution for events with $E_\mu > 10.9$ GeV and hadronic energy < 1.5 GeV for μ^- from the neutrino exposures (solid line) and for μ^+ from antineutrino exposures (dots). The μ^+ distribution is normalized to the μ^- distribution in the range $0.05\,\text{GeV}^2 < p_\perp^2 < 0.1\,\text{GeV}^2$.

IMD signal peak in the μ^- distribution.

The $p_\perp^2$ distributions for quasi-elastic-like neutrino and antineutrino events are expected on very general grounds to be almost equal for isoscalar nuclei [11]. A small difference arises from the fact that the contribution of quasi-elastic strangeness production to the μ^+ distribution is larger than the contribution of quasi-elastic charm production to the μ^- distribution, because of threshold effects. These two reactions are not Pauli suppressed. As described in [10], we subtract from the μ^+ distribution a component modelled without Pauli suppression. For its abundance we took half of the estimated maximal contribution for strangeness production and for the error $1/\sqrt{12}$ of it. A further dissimilarity of the background is due to constructive and destructive vector-axialvector interference in quasi-elastic ν_μ and $\bar{\nu}_\mu$ scattering, respectively, due to parity violation. The vector-axialvector interference is predicted to cause an asymmetry between the μ^- background distribution and the μ^- distribution which is approximately proportional to $p_\perp^2/E_\nu$ [12]. The ratio R of the two distributions should therefore be approximately of the form

$$R \sim 1 + a p_\perp^2 / E_\nu ; \tag{4}$$

a being a constant. E_ν is for the background events

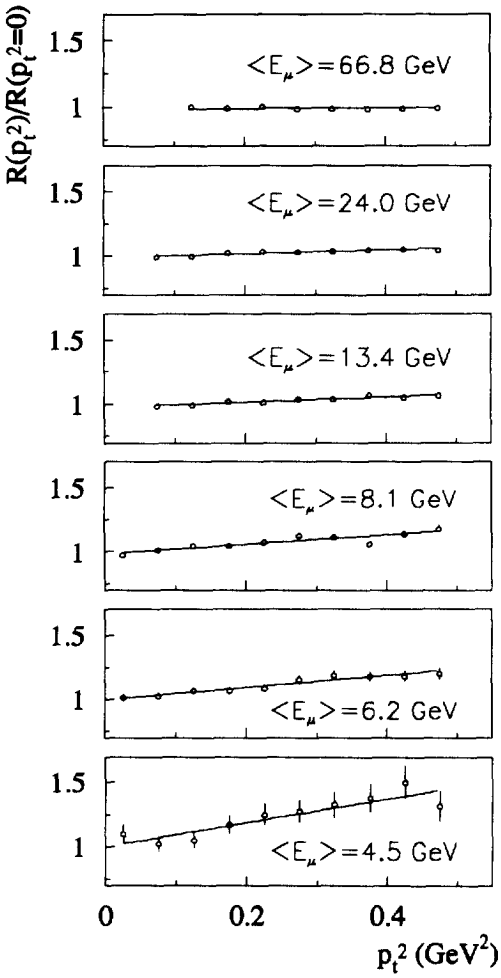

Fig. 2. Ratio R of the background in the μ^- distribution to the μ^+ distribution as a function of $p_\perp^2$ for different muon energies. The errors are statistical. In each energy bin R has been normalized to extrapolate to 1 at $p_\perp^2 = 0$.

close to E_μ.

Fig. 2 shows, for 6 different average muon energies, the $p_\perp^2$ dependence of R, corrected for the difference between strangeness and charm production. To make the comparision of the $p_\perp^2$ dependence for the different muon energy bins easy, all R have been normalized to 1 at $p_\perp^2 = 0$. Without that normalization they would extrapolate to the ratio of neutrino to antineutrino flux in the corresponding energy bin. For muon energies above the IMD threshold the ratio R can only be investigated outside the IMD signal region. We indeed observe a linear behaviour of R with $p_\perp^2$. For muon

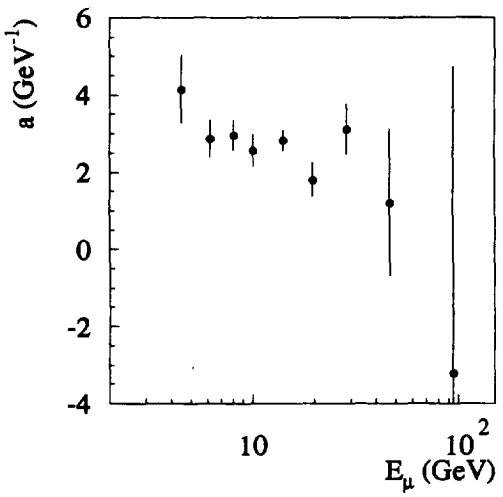

Fig. 3. The slope of the $p_\perp^2$ dependence of R for the different energy intervals of Fig. 2, multiplied by the average muon energies in these intervals as a function of E_μ. The errors are statistical.

energies below the IMD threshold the linear behaviour is seen to continue at low $p_\perp^2$.

Fig. 3 shows the slope of the observed $p_\perp^2$ dependences of R for 9 muon energy bins, multiplied by the average muon energy in these bins. The three lowest energy bins correspond to the three lowest of Fig. 2, while the 6 highest have been pairwise merged in Fig. 2. The mean value of a is $2.7\,\mathrm{GeV}^{-1}$ and a is consistent with being energy independent. One expects for quasi-elastic events $a \approx 2\,\mathrm{GeV}^{-1}$ and for resonance production a higher value, as discussed in [13]. Hence our data show clear evidence for the parity violating vector-axialvector interference term in quasi-elastic neutrino and antineutrino scattering with the properties predicted by the theory.

For the extraction of the IMD signal we have split the data with $E_\mu > 10.9\,\mathrm{GeV}$ into 5 bins of E_μ. Since the signal over background ratio decreases under the IMD peak strongly with $p_\perp^2$, we get the best statistical accuracy with a fit in each E_μ-bin. We use predictions for the $p_\perp^2$ shapes of signal and background. The shape of the IMD signal is calculated by a Monte Carlo simulation. The shape of the background is taken to be the $p_\perp^2$ distribution for μ^+, after correction for strangeness and charm production and for the vector-axialvector interference term. The number of IMD events is obtained in each E_μ bin by a fit of these two components to the observed $p_\perp^2$ distribution for μ^-. We fitted the

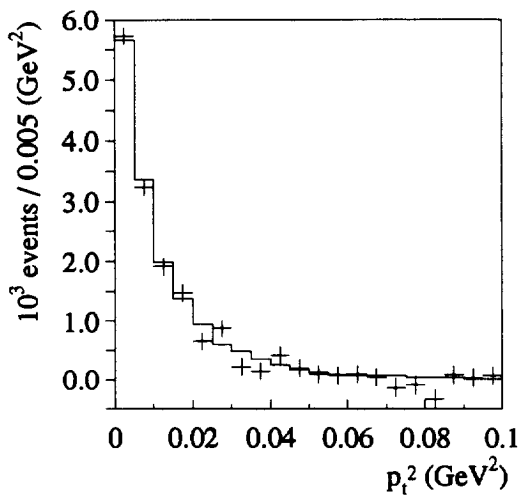

Fig. 4. Distribution of inverse muon decay events as a function of $p_\perp^2$. The solid line represents the expected distribution as simulated by a Monte Carlo calculation.

range $p_\perp^2 < 0.1\ \mathrm{GeV}^2$. Adding up the numbers of IMD events in the 5 E_μ-bins we obtain $15\,758 \pm 324$.

Fig. 4 shows the $p_\perp^2$-distribution for IMD events obtained by subtracting the fitted background distribution from the observed $p_\perp^2$ distribution for μ^-. The result for the 5 muon energy bins are combined. The observed $p_\perp^2$ shape is mainly given by the experimental resolution and is in good agreement with the Monte Carlo prediction, which is also shown. After applying the correction for acceptance we obtained $18,133 \pm 373$ produced IMD events. The main systematic errors in the determination of the IMD signal are due to the following sources: 1) $\pm 1.6\%$ owing to the uncertainty in the difference of strangeness and charm production. 2) $\pm 2.1\%$ owing to a possible difference in the Pauli suppression for neutrino and antineutrino quasi-elastic reactions. This uncertainty was estimated from limits on the difference of the potential energy for protons and neutrons in light nuclei with equal number of protons and neutrons [13]. Our target consists almost entirely of such nuclei. 3) $\pm 1.5\%$ owing to the spread of the estimates of the background contribution when varying the $p_\perp^2$ range used for the determination of the background subtraction. 4) $\pm 0.7\%$ owing to the uncertainty of the acceptance.

The final result for the number of IMD events is:

$$N_{\mathrm{IMD}} = (18.13 \pm 0.37 \pm 0.57) \times 10^3 , \qquad (5)$$

where the first error is statistical and the second one combines the systematic errors in quadrature.

5. Cross section evaluation

The number of IMD events is given by

$$N_{\mathrm{IMD}} = \sigma_{\mathrm{as}} N_{\mathrm{e}} \int \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} E_\nu \left[1 - \frac{m_\mu^2}{2 m_{\mathrm{e}} E_\nu}\right]^2 dE_\nu , \qquad (6)$$

where N_{e} is the number of target electrons and $\mathrm{d}\Phi/\mathrm{d}E_\nu$ is the time integrated neutrino flux as a function of the neutrino energy.

We evaluated the energy-weighted flux integral in Eq. (6) from the number of observed minimum bias (neutral-current and charged-current) events together with the known total neutrino cross sec- tion on isoscalar targets and the shape of the neutrino spectrum as determined from quasi-elastic events. The error on this integral is mainly of systematic origin and contains the following uncertainties: 1) $\pm 2.5\%$ owing to the uncertainty of the total cross section for neutrinos on nuclei. The fit to the experimental data [7] takes into account a possible variation of the cross section slope at low E_ν. 2) $\pm 2.7\%$ owing to the uncertainty of the correction for the loss of minimum bias events due to the 3 GeV cut on the hadronic energy. 3) $\pm 0.4\%$ owing to the uncertainty in the ν_{e}, $\overline{\nu}_\mu$ and $\overline{\nu}_{\mathrm{e}}$ contaminations of the neutrino beam, which also contribute to the minimum bias events. 4) 1.8% owing to the uncertainty of the neutrino energy spectrum.

Adding these contributions in quadrature we obtained for the energy-weighted flux integral $(7.08 \pm 0.29) \times 10^{12}\ \mathrm{GeV\,cm^{-2}}$. With $N_{\mathrm{e}} = 1.60 \times 10^{32}$ the measured asymptotic cross section slope is

$$\sigma_{\mathrm{as}} = (16.01 \pm 0.33 \pm 0.83) \times 10^{-42}\ \mathrm{cm^2\,GeV^{-1}} . \qquad (7)$$

6. Determination of $|g_{\mathrm{LL}}^{\mathrm{S}}|^2$ and $|g_{\mathrm{LL}}^{\mathrm{V}}|^2$

Radiative corrections have to be applied to obtain the Born approximation of the asymptotic cross section slope σ_{as}^0. They have been calculated [14] as a function of the average neutrino energy of IMD events and the detection threshold for inner bremsstrahlung

photons. For our experiment with the values 68 GeV and 1.5 GeV, respectively, they amount to 3%, so that, combining statistical and systematic error in quadrature, we obtained as the final result of our measurement

$$\sigma^0_{as} = (16.51 \pm 0.93) \times 10^{-42}\ \mathrm{cm^2\,GeV^{-1}}, \qquad (8)$$

in good agreement with the Standard Model prediction of $17.23 \times 10^{-42}\,\mathrm{cm^2\,GeV^{-1}}$. The ratio of the measured slope and the slope predicted by the Standard Model is

$$S = 0.958 \pm 0.054. \qquad (9)$$

This result confirms with four times better statistics that of our previous measurement [10], and the result of the CCFR collaboration at FNAL, which used a neutrino beam of higher energy and an iron target [15]. The total errors of our measurement and of the CCFR measurement are almost equal. The error of our result is mostly given by the sytematic uncertainties, while the error of the CCFR measurement is mainly statistical. A somewhat larger systematic uncertainty is expected for our measurement, since we work at lower neutrino energies where the total neutrino cross section on nuclei is less well known and strangeness and charm production differ more.

Assuming left-handed neutrinos as for Eq. (2), the ratio S determines

$$|g^V_{LL}|^2 = 0.958 \pm 0.054, \qquad (10)$$

or, alternatively,

$$|g^V_{LL}|^2 > 0.881 \text{ at } 90\%\ \mathrm{CL}. \qquad (11)$$

Using the constraint of relation (1), this provides an upper limit on $|g^S_{LL}|^2$. We obtained [11]

$$|g^S_{LL}|^2 < 0.475 \text{ at } 90\%\ \mathrm{CL}. \qquad (12)$$

[11] The assumption about the neutrino helicity is actually not needed. Allowing also for a fraction η of right-handed neutrinos in the beam one gets as prediction for S: $S = |g^V_{LL}|^2(1-\eta) + \frac{1}{12}|g^S_{LL}|^2\eta$. The experimental limits on η are $\eta \leq 0.002$ for neutrinos from π decays and $\eta \leq 0.044$ for neutrinos from K decays [7]. Taking for η the maximum experimentally allowed value, one gets slightly tighter limits: $|g^V_{LL}|^2 > 0.895$ and $|g^S_{LL}|^2 < 0.417$, both at 90% CL.

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