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EXPERIMENTAL STUDY OF INVERSE MUON DECAY

(Amsterdam-CERN-Hamburg-Moscow-Rome Collaboration)

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ABSTRACT

The reaction $\nu_{\mu} e^{-} \rightarrow \mu^{-} \nu_e$, the inverse of muon decay, has been studied using an electronic neutrino detector exposed to the CERN SPS horn-focused wide-band neutrino and antineutrino beams. A sample of 171 ± 29 events has been found. The rate agrees with the prediction derived for V-A interaction and for left-handed two-component neutrinos; the ratio is 0.98 ± 0.18 . A search for the reaction $\bar{\nu}_{\mu} e^{-} \rightarrow \mu^{-} \bar{\nu}_e$, allowed by a multiplicative lepton number conservation, gave a limit of $\sigma(\bar{\nu}_{\mu} e^{-} \rightarrow \mu^{-} \bar{\nu}_e) / \sigma(\nu_{\mu} e^{-} \rightarrow \mu^{-} \nu_e) < 0.09$, with 90% confidence.

1. INTRODUCTION

A study of the reaction

$$\nu_{\mu} e^{-} \rightarrow \mu^{-} \nu_e, \quad (1)$$

the inverse of muon decay, provides information about the V-A structure of the leptonic charged-current interaction [1], the two-component neutrino theory [2], and about the conservation law of lepton charge [3]. This information cannot be obtained by investigating muon decay without the observation of the decay neutrinos. Until recently [4] this reaction had not been investigated because the threshold energy is rather high (11 GeV) and because of the low cross-section.

The differential cross-section [5] of reaction (1) for $s \gg m_{\mu}^2$ can be expressed in terms of $y = E_{\mu}/E_{\nu}$ in the form

$$\frac{d\sigma}{dy} = \frac{G^2}{\pi} \frac{s}{8} [(1+P)(1-\lambda)y^2 + (1-P)(1+\lambda)], \quad (2)$$

with $\lambda = -2\text{Re}(g_V^* g_A)/(|g_V|^2 + |g_A|^2)$ and $P = N(\nu_R) - N(\nu_L)/[N(\nu_R) + N(\nu_L)]$, the neutrino polarization.

A value of $\lambda = 1$ would be a proof of the V-A structure of the interaction, and $P = -1$ of left-handed two-component neutrinos.

Theories of multiplicative conservation of the lepton number [6] allow reaction (1) to be induced also by "wrong" neutrinos:

$$\bar{\nu}_{\mu} e^{-} \rightarrow \mu^{-} \bar{\nu}_e. \quad (3)$$

In modern versions of these theories [7], constructed by appending spontaneously broken lepton permutation invariance to the SU(2) gauge group, the rate, Γ of reaction (3) can be predicted in terms of the mass m_H of a Higgs field carrying lepton flavour,

$$\Gamma(3) \sim G_F^2 (m_T/m_H)^4.$$

We have studied reaction (1) and searched for reaction (3) using an electronic neutrino detector [8], exposed to the horn-focused wide-band neutrino and anti-neutrino beams produced by 400 GeV protons from the CERN Super Proton Synchrotron (SPS) with a maximum flux around 15 GeV. An isometric view of part of the detector

is shown in fig. 1. It consists of a segmented ionization calorimeter surrounded by a magnetized iron frame, and of a muon spectrometer. The calorimeter consists of 78 modules, each with the following structure along the beam direction: a marble plate, 8 cm thick and of $3 \times 3 \text{ m}^2$ cross-sectional area; a plane of 128 proportional drift tubes [9], each having dimensions of $3 \times 3 \text{ cm}^2$ in cross-section and 4 m in length; and a plane of 20 plastic scintillators, each 3 cm thick and $15 \times 300 \text{ cm}^2$ in surface area, oriented at 90° with respect to the tubes.

The tubes are used to measure the muon track parameters; the polar angle is measured with a resolution of $\pm 2.5 \text{ mrad}$ at 26 GeV/c. The scintillators measure the energy of hadronic showers produced in the calorimeter.

Each marble plate is surrounded by a magnetized iron frame, 45 cm wide and 8 cm thick. A toroidal field in the frame focuses large-angle muons toward the calorimeter. The proportional drift tubes, which extend into the gaps between successive iron frames, are used to track these muons for identification and momentum measurement.

The target calorimeter is followed by four toroidal iron magnets used to identify and momentum-analyse forward-going muons. The magnets are segmented into disks, 5 cm thick in the first module and 15 cm thick in the three following modules, for a total iron length of 3 m. The iron disks have an outer radius of 185 cm, and a central hole of 16.7 cm radius for the coils. Eighteen planes of proportional drift tubes, interspersed between the disks, are used to determine the muon momentum with a resolution of $\sim 16\%$.

The detector was triggered by requiring that at least four scintillator planes be hit, that the detected ionization be larger than 50 MeV, and that a track penetrated the muon spectrometer.

Events of reaction (1) can be identified by the particular characteristics of the kinematics of neutrino-electron scattering compared with the kinematics of neutrino-nucleon scattering. The muon in reaction (1) is expected to be emitted at very small angles, according to

$$E_\mu \theta_\mu^2 = 2m_e(1 - y) .$$

For $E_\mu > 11$ GeV (the threshold energy), θ_μ is smaller than 10 mrad, and no visible recoil is expected. Consequently, the analysis aimed at selecting single-muon events without visible hadron recoil.

A fiducial volume was defined to ensure adequate track measurements. Muon tracks starting in any one of the submodules 3 to 69 were accepted, thus leaving at least nine planes before the muon spectrometer for measuring their angle. The tracks were accepted over the entire surface of the scintillator planes ($|y, z| < 150$ cm), and were required to have a distance from the beam axis at the entrance to the muon spectrometer of $25 < R \leq 180$ cm, to ensure full detection efficiency.

Two different sets of criteria have been used to select $\nu_\mu (\bar{\nu}_\mu)$ -induced single-muon events. The first set (criteria I) aimed at detecting events due to reaction (1) and to quasi-elastic scattering:

$$\nu_\mu n \rightarrow \mu^- p, \quad (4)$$

with good efficiency. The mean energy loss of a muon from reaction (1) or (4) is 8.5 MeV per scintillator plane. Events were selected i) if they had less than 92 MeV visible energy in the first six planes of scintillators; ii) if the muon was negative (positive) for neutrino (antineutrino) runs; and iii) if the time of flight measured between the scintillation counters in the last magnet of the muon spectrometer and the scintillators in the last plane of the calorimeter was compatible with a track following the direction of the neutrino beam and not with a cosmic-ray muon entering the spectrometer in the opposite direction. A total of 9,380 neutrino-induced and of 24,279 antineutrino-induced events met with these criteria.

Several checks have been performed to ensure that the sample of events selected according to criteria I is due to quasi-elastic scattering and that the contamination by other channels is small. i) The ratio of inclusive one-muon events to quasi-elastic candidates was found to increase linearly with neutrino energy, as expected for the linearly rising total cross-sections and the constant quasi-elastic cross-sections. This test is, however, valid for any exclusive channel and does not determine the contamination of the selected sample by one-pion production:

$$\nu_{\mu} N \rightarrow \mu^{-} \pi N . \quad (5)$$

ii) The distribution as a function of neutrino energy is in good agreement with other measurements on exclusive channels performed in the same beam, e.g. with measurements in BEBC [10] of the reaction

$$\nu_{\mu} p \rightarrow \mu^{-} \Delta^{++}(1235) \quad (6)$$

and with the calculated neutrino flux spectrum [11]. iii) The ratio of the number of quasi-elastic candidates to inclusive one-muon events has been calculated to be $(2.4 \pm 0.2) \times 10^{-2}$ and was found to be $(3.7 \pm 0.4) \times 10^{-2}$, whereas the ratio of one-pion production in reaction (5) to inclusive one-muon reactions is expected to be $(4.8 \pm 0.8) \times 10^{-2}$. The error of the predicted ratios is estimated taking into account the systematic uncertainties of the calculated neutrino flux spectrum. The contamination of the sample due to reaction (5) is therefore smaller than 35%.

iv) Above $E_{\nu} = 10$ GeV the q^2 dependence of quasi-elastic scattering and of reaction (5) is expected to be energy independent and identical for ν_{μ} and $\bar{\nu}_{\mu}$ [12]. At small angles, q^2 is well approximated by $p_T^2(\mu)$, the muon transverse momentum squared. Figure 2 shows the q^2 distributions of μ^{-} and μ^{+} events, obtained in neutrino and antineutrino runs, respectively, after normalization to equal event numbers in the range

$$0.02 < q^2 < 1.0 \text{ GeV}^2 . \quad (7)$$

The distributions have the same shape in the range of eq. (7), as expected for quasi-elastic scattering and for reaction (5), and their difference is statistically compatible with zero. In the presence of quasi-elastic scattering and of reaction (5) alone, we expect that the two distributions remain equal even for $q^2 < 0.02 \text{ GeV}^2$. The excess of μ^{-} events observed in this region,

$$N_{\nu}(\mu^{-}) - N_{\bar{\nu}}(\mu^{+}) = 391 - 273 = 118 \pm 23 ,$$

is attributed to the inverse muon decay reaction (1).

We have made a number of checks to ensure that this attribution is compelling. More restrictive criteria (criteria II) have been defined for selecting recoil-less

single-muon events due to reaction (1). The visible energy in the first six planes of scintillators was required to be less than 90 MeV in total, less than 18 MeV in each of the first three planes, and the sum in the first two planes less than 20 MeV. If more than one proportional drift tube was hit in one of the first three planes, this requirement was reduced to 10 MeV in the corresponding gap in order to discriminate between a recoil track and a delta-ray.

These criteria and the previous ones reduce the efficiency for detecting muons because of the large fluctuations in energy loss due to delta-ray production and bremsstrahlung. The efficiency has been determined experimentally by applying criteria I and II to later parts of the same tracks, starting at least 18 submodules after the vertex, with the result

$$\epsilon(I) = 0.968 \pm 0.002, \quad \epsilon(II) = 0.880 \pm 0.003. \quad (8)$$

The more restrictive criteria II impose a limit of $q^2 < 0.1 \text{ GeV}^2$ on the detection of quasi-elastic ν_μ and $\bar{\nu}_\mu$ scattering. Above this value of q^2 , proton recoils from $\nu_\mu n \rightarrow \mu^- p$ start to be rejected, whereas neutron recoils from $\bar{\nu}_\mu p \rightarrow \mu^+ n$ have an even smaller probability of being detected. We have therefore restricted the normalization of the $N_V(\mu^-)$ and the $N_V(\mu^+)$ distributions to the range

$$0.02 < q^2 < 0.1 \text{ GeV}^2.$$

For $q^2 < 0.02 \text{ GeV}^2$ we again observe an excess of μ^- events,

$$N_V(\mu^-) - N_V(\mu^+) = 267 - 156 = 111 \pm 18.$$

A summary of this analysis is given in table 1. Correcting for the muon efficiencies (8), we find that the results obtained using the two different criteria are in good agreement, confirming the recoil-less characteristic of reaction (1).

The observed rate of inverse muon decay has been further corrected for the efficiency of the selection criteria ($q^2 < 0.02 \text{ GeV}^2$ and $p_\mu > 10/\text{GeV}/c$), ϵ_{cut} , using the experimentally observed E_V spectrum and simulating the experimental resolutions of the detector, and for the efficiency of the fitting of the muon track ϵ_{fit} :

$$\epsilon = \epsilon_{\text{cut}} \times \epsilon_{\text{fit}} = (0.787 \pm 0.020)(0.935 \pm 0.002) = 0.736 \pm 0.019.$$

Using the result for the strict recoil-less selection (criteria II) (see table 1), the rate of reaction (1) is found to be

$$N(\nu_{\mu} e^{-} \rightarrow \mu^{-} \nu_e) = 171 \pm 29$$

for a total acceptance-corrected number of inclusive one-muon events with $E_{\text{vis}} > 10$ GeV of $(2.99 \pm 0.11) \times 10^5$, or

$$R_{\text{exp}} = \frac{N(\nu_{\mu} e^{-} \rightarrow \mu^{-} \nu_e)}{N(\nu_{\mu} N \rightarrow \mu^{-} X)} \Big|_{E_{\text{vis}} > 10 \text{ GeV}} = \frac{171 \pm 29}{(2.99 \pm 0.11) \times 10^5} = (5.7 \pm 1.0) \times 10^{-4} .$$

The predicted number of inverse muon decays is obtained by integrating Eq. (2) over the observed E_{ν} spectrum,

$$N = \frac{N_0}{32} [(1 + P)(1 - \lambda)C + 8(1 - P)(1 + \lambda)] , \quad (9)$$

with $C = 2.98$ given by the integrated neutrino spectrum, and $N = N_0$ the number of events expected for $\lambda = 1$, $P = -1$ (V-A).

Evaluating Eq. (9) for V-A interaction, corresponding to $P = -1$ and $\lambda = 1$, for V+A interaction, corresponding to $P = 1$ and $\lambda = -1$, the following rates are predicted for reaction (1):

$$N(\text{V-A}) = 175 \pm 5$$

$$N(\text{V+A}) = 65 \pm 2 .$$

These numbers should be compared with $N_{\text{exp}} = 171 \pm 29$. The V-A interaction and left-handed neutrinos are clearly favoured,

$$\frac{R_{\text{exp}}}{R_{\text{V-A}}} = 0.98 \pm 0.18 ,$$

whereas the possibility of a V+A interaction and right-handed neutrinos seems excluded.

Figure 3 shows the result of this experiment in terms of upper limits in the P - λ plane; a previous result obtained by the Gargamelle Collaboration [4] is shown as well. Figure 4a shows the q^2 distribution of the sample of events obtained by the normalized difference of $N_{\nu}(\mu^{-})$ and $N_{\bar{\nu}}(\mu^{+})$, using the strict recoil criteria (II); and fig. 4b shows the μ^{-} momentum distribution. Both confirm the expected behaviour of reaction (1).

We conclude that this study of the inverse muon decay reaction confirms the V-A structure of the leptonic charged-current interaction and the two-component theory with left-handed neutrinos.

A search for candidates of the "wrong" reaction (3) has been made using the methods described above. A total of 2358 recoil-less single μ^- events have been observed in antineutrino runs, and the excess of μ^- events with $p_\mu > 10$ GeV/c and $q^2 < 0.02$ GeV² was found to be 40 ± 9 .

The antineutrino beam is contaminated with neutrinos, as measured by the sample of μ^- events. The energy spectra of the ν_μ beam and of the $\bar{\nu}_\mu$ beam and of its ν_μ contamination are found to be of very similar shape. Hence, scaling from the neutrino beam, we expect the following contribution of reaction (1) to the observed excess:

$$111 \times \frac{2358}{9380} = 27.9 \text{ events.}$$

From the other allowed inverse muon decay reaction [5]

$$\bar{\nu}_e e^- \rightarrow \mu^- \bar{\nu}_\mu \quad (10)$$

we also expect a contribution, due to the $\bar{\nu}_e$ contamination of the antineutrino beam:

$$N(10) = 27.9 \times \frac{N(\bar{\nu}_e)}{N(\nu_\mu)} \times \frac{\bar{E}(\bar{\nu}_e)}{\bar{E}(\nu_\mu)} \times \frac{\sigma(\bar{\nu}_e e)}{\sigma(\nu_\mu e)} = 2.2 \text{ events,}$$

with $N(\bar{\nu}_e)/N(\nu_\mu) = 0.11$ and $\bar{E}(\bar{\nu}_e)/\bar{E}(\nu_\mu) = 1.89$ derived from calculated neutrino flux spectra [10], and $\sigma(\bar{\nu}_e e^-)/\sigma(\nu_\mu e) = 3/8$ for V-A interaction [5]. The events that could be due to reaction (3) are thus

$$40 - 27.9 - 2.2 = 10 \pm 10.$$

By assuming a multiplicative lepton number conservation model [6], which allows reaction (3) to take place, we can evaluate the ratio of the cross-section, and find

$$\frac{\sigma(\bar{\nu}_\mu e \rightarrow \mu^- \bar{\nu}_e)}{\sigma(\nu_\mu e \rightarrow \mu^- \nu_e)} = \frac{N(3)/N_{\bar{\nu}}(\mu^+)}{N(1)/N_{\nu}(\mu^-)} < 0.09 \quad (11)$$

at the 90% confidence level. Our results seem therefore to exclude these models.

According to modern versions of these theories [7] the rate expected for reaction (3)

depends on the mass of a Higgs field m_H . In this case, the above result (11) indicates that $m_H > 3.3$ GeV (90% confidence limit).

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Table 1

Summary of data analysis of recoil-less events

Sample	Recoil Criteria I	Recoil Criteria II
Single μ^- with $q^2 < 0.02 \text{ GeV}^2$ $p_\mu > 10 \text{ GeV}$	391	267
Background a) from quasi-elastic scattering	273 ± 11	156 ± 10
Candidates of inverse μ decay	118 ± 23	111 ± 19
Correction for recoil criteria	$\frac{118}{0.968} = 122 \pm 23$	$\frac{111}{0.88} = 126 \pm 22$
Rate of inverse μ decay b)	$\frac{122}{0.736} = 166 \pm 32$	$\frac{126}{0.736} = 171 \pm 29$

- a) Estimated by single μ^+ events observed in the $\bar{\nu}_\mu$ beam and normalized to μ^- events for $0.02 < q^2 < 1 \text{ GeV}^2$ for criteria I and for $0.02 < q^2 < 0.1 \text{ GeV}^2$ for criteria II.
- b) Corrected for $q^2 < 0.02 \text{ GeV}^2$, $p_\mu > 10 \text{ GeV}/c$ and muon fitting efficiency.

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Figure captions

Fig. 1 : Partial view of the fine-grain calorimeter. Each subunit is composed of a marble plate of $3 \times 3 \text{ m}^2$ surface area and 8 cm thickness, a layer of 20 scintillators 15 cm wide, and a layer of 128 proportional drift tubes 3 cm wide. The fine-grain calorimeter is surrounded by a frame of magnetized steel and followed by four toroidal iron magnets, each 75 cm thick, to detect muons.

Fig. 2 : q^2 dependence of single μ^- and single μ^+ events without visible recoil, normalized to equal numbers for $0.02 < q^2 < 1.0 \text{ GeV}^2$. The inset shows the same data in bins of 0.01 GeV^2 .

Fig. 3 : 90% confidence limits on neutrino beam polarization:

$$P = \frac{N(\nu_R) - N(\nu_L)}{N(\nu_R) + N(\nu_L)}$$

and $\lambda = -2 \text{ Re } (g_V^* g_A) / (|g_V|^2 + |g_A|^2)$ deduced from the observed rate of the inverse muon decay reaction. Also shown is a previous 90% confidence limit obtained by the Gargamelle Collaboration (ref. 4).

Fig. 4 : (a) Observed q^2 distribution of the difference $N_V(\mu^-) - N_V(\mu^+)$, normalized to equal rate for $0.02 < q^2 < 0.1 \text{ GeV}^2$, and the prediction for inverse muon decay, assuming V-A interaction.

(b) Observed μ^- momentum distribution of the difference

$N_V(\mu^-; q^2 < 0.02 \text{ GeV}^2) - N_V(\mu^-, q^2 > 0.03 \text{ GeV}^2)$ normalized to

111 events and prediction for inverse muon decay, assuming V-A interaction.

Fig. 1

Fig. 2

Fig. 3

Fig. 4