EXPERIMENTAL STUDY OF INVERSE MUON DECAY

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ABSTRACT

The reaction $\nu_\mu e^- \to \mu^- \nu_e$, 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 $\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_e$, allowed by a multiplicative lepton number conservation, gave a limit of $\sigma(\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^- \nu_e) < 0.09$, with 90% confidence.

1. INTRODUCTION

A study of the reaction

$$\nu_\mu e^- \to \mu^- \nu_e \quad , \tag{1}$$

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

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

with $\lambda = -2\mathrm{Re}(g_V^* g_A)/(|g_V|^2 + |g_A|^2)$ 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:

$$\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_e \quad . \tag{3}$$

We have studied reaction (1) and searched for reaction (3) using an electronic neutrino detector 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 3×3 m^2 cross-sectional area; a plane of 128 proportional drift tubes[7], each having dimensions of 3×3 cm^2 in cross-section and 4 m in length; and a plane of 20 plastic scintillators, each 3 cm thick and 15×300 cm^2 in surface area, oriented at 90° with respect to the tubes.

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

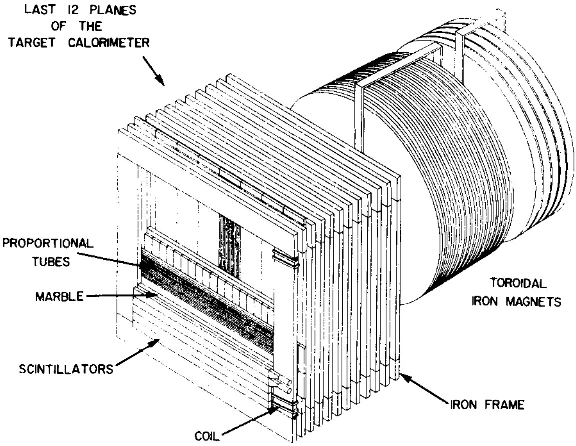


Fig. 1 Partial view of the fine-grain calorimeter

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

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.

The selection criteria aimed at detecting events due to reaction (1) and to quasi-elastic scattering:

$$\nu_\mu n \rightarrow \mu^- p \quad , \tag{4}$$

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 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-section. This test is, however, valid for any exclusive channel and does not determine the contamination of the selected sample by one-pion production:

$$\nu_\mu N \to \mu^- \pi N \quad . \tag{5}$$

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[8] of the reaction

$$\nu_\mu p \to \mu^- \Delta^{++}(1235) \tag{6}$$

and with the calculated neutrino flux spectrum[9].

iii) 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 $\bar{\nu}_\mu$ [10]. 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

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

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 $q^2 < 0.02$ GeV^2. The excess of μ^- events observed in this region,

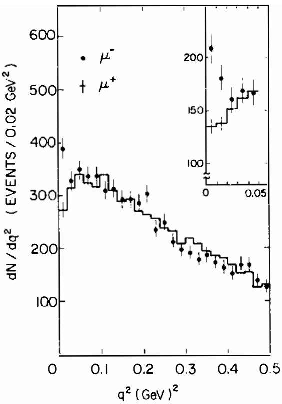


Fig. 2 q^2 dependence of single μ^- and single μ^+ events without visible recoil

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

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

The observed rate of inverse muon decay has been further corrected for the efficiency of the selection criteria ($q^2 < 0.02$ GeV^2 and $p_\mu > 10$/GeV/c), the efficiency of the recoil criteria and the muon track fitting efficiency. The rate of reaction (1) is found to be

$$N(\nu_\mu e^- \to \mu^- \nu_e) = 171 \pm 29$$

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

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

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

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

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

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

$$N(V+A) = 65 \pm 2 \quad .$$

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

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

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 $N_{\bar{\nu}}(\mu^+)$ and Fig. 4b shows the μ^- momentum distribution. Both confirm the expected behaviour of reaction (1).

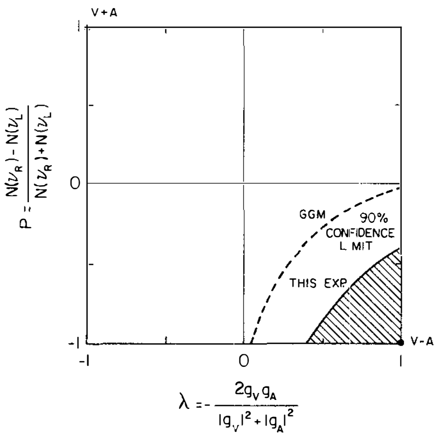
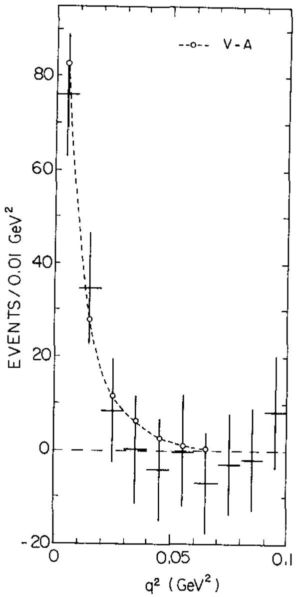
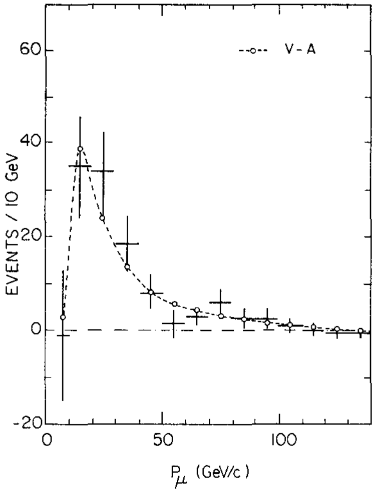


Fig. 3 90% confidence limits on P and λ deduced from the observed rate of the inverse muon decay reaction.



(a)



(b)

Fig. 4 (a) Observed q^2 distribution of the difference $N_\nu(\mu^-) - N_{\bar\nu}(\mu^+)$ and the prediction for inverse muon decay, assuming V-A interaction;

(b) Observed μ^- momentum distribution and the prediction for inverse muon decay, assuming V-A interaction.

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 2,358 recoil-less single μ^- events have been observed in antineutrino runs, and the excess of μ^- events with $p_\mu > 10$ GeV/c and $q^2 < 0.02$ GeV^2 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 a contribution of 27.9 events of reaction (1) to the observed excess. From the other allowed inverse muon decay reaction[5)]

$$\bar\nu_e e^- \rightarrow \mu^- \bar\nu_\mu \qquad (9)$$

we expect a contribution of 2.2 events, due to the $\bar{\nu}_e$ contamination of the antineutrino beam. The events that could be due to reaction (3) are thus

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

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

$$\frac{\sigma(\bar{\nu}_\mu e \rightarrow \mu^- \bar{\nu}_e)}{\sigma(\nu_\mu e \rightarrow \mu^- \nu_e)} < 0.09 \tag{10}$$

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

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