POLARIZATION OF POSITIVE MUONS PRODUCED IN
HIGH-ENERGY ANTINEUTRINO INTERACTIONS

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(Submitted to Physics Letters B)

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ABSTRACT

The polarization of positive muons produced in charged current interactions of high-energy antineutrinos in iron has been measured at an average momentum transfer of $\langle Q^2 \rangle = 3.2 \text{ GeV}^2$. The muon spin is found to be oriented forward with respect to the muon momentum vector with an average polarization of 1.09 ± 0.22 , consistent with helicity +1. It is concluded that the weak leptonic charged current retains its dominant vector and axial vector structure at high energies.

The Lorentz structure of the charged current weak interaction has so far been studied in decay processes. In particular, the muon helicity in pion [1] and kaon [2] decays, which are the main sources of high-energy neutrino beams, has been measured, and it is known that the charged current is dominated by vector and axial vector terms. No corresponding measurements exist in the study of high-energy neutrino interactions, where the centre of mass energy is substantially higher and where *a priori* other current forms might also become important. The results which exist so far, such as the inelasticity or y-distributions in ν - and $\bar{\nu}$ -nucleon scattering [3,4], are in fact, consistent with the expectations of V and A currents, namely with a V-A structure. However, it has been pointed out [5] that such y-distributions can also be described by appropriate mixtures of S, P, and T interactions. Measurements of the helicity of muons produced in neutrino interactions can resolve the question [6], as currents of V or A type preserve the helicity of the incident neutrino, whereas interactions of S, P, or T type flip the neutrino helicity. Hence positive muons from antineutrino interactions are expected to have positive helicity if the interaction is V or A, and negative helicity if the interaction is S, P, or T.

This paper reports first measurements of the polarization of muons produced by the interaction of antineutrinos with iron, according to the reaction

The experimental arrangement consisted of two parts, the target and the polarimeter, exposed to the horn-focused wide-band antineutrino beam produced by 330 GeV protons from the CERN Super Proton Synchrotron (SPS) with a maximum antineutrino flux around 25 GeV. A schematic view of the set-up is shown in fig. 1.

The target [7] consisted of 19 magnetized modules, with a toroidal field of 16.5 kG average strength, each followed by a three-plane drift chamber [8] to measure the muon track parameters. A module was made of iron plates 3.75 m in diameter, for a total cross-thickness of 75 cm. Layers of scintillators were inserted every 5 or 15 cm of iron to provide a calorimetric measurement of the hadronic energy. A muon crossing one module of the target released typically

1.2 GeV. Positive muons were focused by the toroidal field towards the polarimeter. Approximately 5% of the muons produced in the target stopped inside the polarimeter.

The polarimeter [9] had a transverse cross-section of $3 \times 3 \text{ m}^2$ and consisted of 78 submodules, each one with the following structure along the beam direction: an 8 cm thick marble (CaCO_3) plate for stopping the muon; a 3 cm thick plane composed of 128 proportional drift tubes [10] for observing the muon track; and a 3 cm thick plane composed of 20 plastic scintillators for detecting the positron from muon decay. This polarimeter structure was surrounded by an iron frame magnetized in such a way as to produce a magnetic field of 58 G transverse to the beam direction inside the polarimeter volume. The field was measured and found to be homogeneous to within $\pm 3\%$.

The longitudinal projection of the spin of a stopped muon precessed with a period of $1.3 \text{ } \mu\text{s}$ in a plane perpendicular to the plates of the polarimeter. Positrons from muon decay were detected in a scintillator plane, either backward (upstream) or forward (downstream) with respect to the marble plate in which the muon had stopped (fig. 2). Because of the well-established V-A interaction in muon decay ($\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$), high-energy positrons are emitted preferentially in the direction of the muon spin. It is therefore expected to observe a time-dependent forward-backward asymmetry of positrons.

The energy deposited by a positron in the scintillators, and the time which elapsed between the stopping of a muon and the appearance of a positron, were recorded. The arrangement of detector elements described above did not allow any distinction between a muon stopped in a marble plate or in the preceding scintillator plane. Thus decay positrons from muons which stopped in one of the scintillators were always assigned as backward decays (fig. 2).

The method of spin precession is insensitive to systematic forward-backward asymmetries of the apparatus and allows determination of the degree of longitudinal polarization from the amplitude of the time-dependent relative backward-forward positron yield.

Since muons may suffer some depolarization in the stopping material as they come to rest, a comparative study was made of the polarization analysing power of the marble structure described above and of an identical polarimeter structure using carbon plates as stopping material. This experimental study was done using polarized muons from decays in flight of 140 MeV/c pions at the CERN Synchro-cyclotron (SC). The relative polarization analysing power of the marble structure normalized to that of the carbon structure was found to be 0.96 ± 0.08 . Since carbon is known to be non-depolarizing [11] [residual polarization = $(100 \pm 6)\%$] it can be concluded that the residual polarization of muons after stopping in marble is $(96 \pm 10)\%$.

During a first $\bar{\nu}_\mu$ beam exposure, 13,000 events were recorded fulfilling the following conditions:

- i) a trigger was found by the target detector corresponding to an energy release of at least 7 GeV in addition to a veto signal from the anticounter in front of the target (excluding upstream muons);
- ii) a track was required to penetrate into the polarimeter and stop there in a fiducial volume of $2.7 \times 2.7 \times 4 \text{ m}^3$. The polarimeter was under construction during this period and did not, therefore, have the full volume available.

A subsample of 250 events was fully reconstructed in the target. This subsample was studied in order to estimate possible biases and the kinematical region accepted, with the following results:

- i) negative muons due to neutrino background in the antineutrino beam or to π^-/K^- decay muons not absorbed in the shielding contributed less than 1%;
- ii) 12% of the events showed a positive muon entering the target from the sides. These muons were either produced by antineutrinos in the shielding or they came from the decay of wrong-sign parents (π^+ , K^+) and were not absorbed in the shielding.

The averages of some characteristic kinematical quantities of the reconstructed events are listed in Table 1.

In 3400 out of the 13,000 events, a decay positron was recorded in a time window of $0.56 < t < 4.38 \mu\text{s}$ after the muon came to rest. The observed time distribution of the positrons yielded a muon mean lifetime of $2.16 \pm 0.08 \mu\text{s}$, in good agreement with that expected for positive muons. The observed time dependence of the backward-forward asymmetry,

$$R(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = R_0 \cos(\omega t + \phi) + R_1, \quad (1)$$

is shown in fig. 3.

The magnetic field of 58 G induced a precession frequency $\omega = 4.92 \text{ MHz}$. The phase ϕ was expected to be $\phi = 0$ for negative helicity and $\phi = -\pi$ for positive helicity. The oscillation amplitude R_0 is proportional to the magnitude of longitudinal polarization P and the polarimeter analysing power α ($R_0 = \alpha \cdot P$). Positrons from muons which stopped and decayed in a scintillator created an offset R_1 and also diminished the oscillation amplitude R_0 with respect to an amplitude R_0^M , which would be expected had no muon stopped in a scintillator. These effects were parametrized in the following way:

$$R(t) = \frac{\epsilon_M}{\epsilon_M + \beta} R_0^M \cos(\omega t + \phi) + \frac{\beta}{\epsilon_M + \beta}, \quad (2)$$

where

$$\epsilon_M = \frac{\text{Number of } e^+ \text{ from } \mu\text{-stops in marble}}{\text{Number of } \mu\text{-stops in marble}}$$

$$\beta = \frac{\text{Number of } e^+ \text{ from } \mu\text{-stops in scintillator}}{\text{Number of } \mu\text{-stops in marble}}.$$

Values for R_0 , ϕ , and R_1 as determined by a fit are shown in Table 2, together with the over-all (marble + scintillator) positron detection efficiency ϵ and the derived quantities β , ϵ_M , R_0^M . The experimental value for the oscillation phase ϕ is in excellent agreement with $-\pi$ and shows that the muons have a positive helicity. This result shows that S, P, or T terms do not dominate the interaction.

To determine the absolute value of the polarization P it is necessary to know the polarimeter analysing power α . To achieve this, a detailed Monte Carlo calculation was performed. In this calculation a 10% depolarization [12] during the

passage of muons through the absorbing material (iron + marble) was taken into account. Based on the results of the polarization measurements with muons from pion decay described above, it was further assumed that muons do not suffer any depolarization at the very end of their range when they come to rest in marble. The decay positron was followed through the polarimeter material, taking into account bremsstrahlung, pair creation, and Compton scattering. The resulting spectrum of energy loss by positrons in the scintillators was found to be in good agreement with the experimentally observed one. Table 2 gives a comparison of measured parameters and their values obtained by Monte Carlo simulation assuming helicity +1.

The helicity-independent parameters (R_1 , ϵ , β , ϵ_M) are in good agreement, and it may be concluded that muon decay and propagation of positrons through the polarimeter material are well described by the Monte Carlo simulation.

Normalizing the oscillation amplitude R_0 to the value predicted for $P = +1$, taking account of the observed phase value, yields a longitudinal polarization of $P = + (1.09 \pm 0.22)$. The quoted error includes a statistical error of $\Delta P = \pm 0.20$ and a systematic error of $\Delta P = \pm 0.10$ due to the uncertainty in the residual polarization of muons after stopping in marble.

The fact that 12% of the events have not been positively identified as μ^+ from antineutrino interactions may cause a small difference between the measured polarization and the genuine polarization of leading muons from antineutrino interactions. Assuming the two extreme possibilities that all 12% are either helicity +1 or -1, respectively, restricts the polarization of leading muons to $+1.07 < P < +1.36$. The shift of the polarization to a value significantly greater than one, indicates that the assumption that all 12% are due to muons from π^+/K^+ decays ($P = -1$) is not very probable.

It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental errors the helicity is found

to be +1, consistent with a purely V,A form of the interaction. An upper limit $\sigma_{S,P,T}/\sigma_{\text{tot}} < 18\%$ at the 95% confidence level can be set on S, P, or T contributions to charged current interactions at an average momentum transfer of $\langle Q^2 \rangle = 3.2 \text{ GeV}^2$.

Further experimental work is planned in order to investigate a possible variation of the polarization as a function of the inelasticity y induced by weak spin-flipping terms.

This experiment could be performed only thanks to the help of the CERN-Dortmund-Heidelberg-Saclay Collaboration, who built the massive neutrino detector, used as target in the present experiment, and operated it during data taking. We are very grateful for this essential contribution. We most sincerely thank our many technical collaborators and the members of the SPS staff for the operation of the accelerator.

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Table 1

Average values of some kinematical quantities characterizing the antineutrino interactions and the μ^+ detected in the experiment

$\langle p_\mu \rangle$	$= 16.1 \pm 0.35 \text{ GeV/c}$
$\langle E_{\text{tot}} \rangle$	$= 26.5 \pm 0.85 \text{ GeV}$
$\langle E_{\text{had}} \rangle$	$= 10.2 \pm 0.75 \text{ GeV}$
$\langle x \rangle$	$= 0.19 \pm 0.01$
$\langle y \rangle$	$= 0.34 \pm 0.01$
$\langle Q^2 \rangle$	$= 3.2 \pm 0.3 \text{ GeV}^2$

Table 2

Comparison of the values of the parameters in eqs. (1) and (2) determined by fitting the data and by the Monte Carlo simulation

	Data	Monte Carlo P = +1
R_0	0.14 ± 0.02	0.14 ± 0.01
ϕ	-3.1 ± 0.2	-3.14
R_1	0.32 ± 0.02	0.36 ± 0.01
ϵ	0.39 ± 0.01	0.38 ± 0.01
R_0^M	0.21 ± 0.03	0.22 ± 0.02
ϵ_M	0.30 ± 0.02	0.28 ± 0.01
β	0.14 ± 0.01	0.16 ± 0.01

Figure captions

- Fig. 1 : Layout of the polarization experiment.
- Fig. 2 : Schematic view of the polarimeter structure with examples of μ^+ stopping and decaying in marble (M) and in scintillator (S). The stopping μ track is measured using the proportional drift tubes (T).
- Fig. 3 : Observed time dependence of relative backward-forward positron asymmetry. The sinusoidal function is the best fit of eq. (1) to the experimental points corresponding to the results given in Table 2.

Fig. 1

F = Forward e^+
 B = Backward e^+

M = Marble
 T = Prop. tubes
 S = Scintillators

Fig. 2

Fig. 3