RESULTS FROM THE HARVARD, PENNSYLVANIA, WISCONSIN-FNAL EXPERIMENT

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Neutral Currents

A brief survey is given of the data on muonless events/neutral currents accumulated in this experiment.

The first result on muonless events was announced at the Bonn and Aix-en-Provence Conferences and later published[1]. The result for the ratio R of neutral current to charged current cross-sections was

$$R = 0.23 \pm 0.09$$

in a beam containing both ν and $\bar{\nu}$.

More recent experiments have been carried out with a modified apparatus (Fig. 1) and different beams.

The modifications to the apparatus were

(i) the addition of 35 cm. of iron immediately downstream of the ionization calorimeter to form a muon identifier (μ_1) consisting of counter B and spark chamber SC4

(ii) doubling the area of the counter C and the replacement of the 5.3 m^2 narrow gap chambers in the magnetic spectrometer by 8.4 m^2 wide gap chambers to increase the solid angle of the second muon identifier (μ_2).

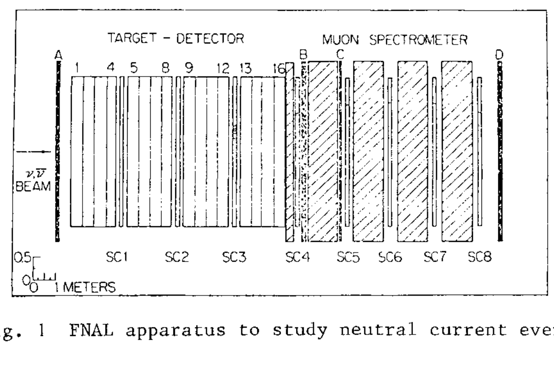

Fig. 1 FNAL apparatus to study neutral current events.

To use the counter B or SC4 as a muon identifier it is necessary to measure the probability ε_p that hadrons penetrate the μ_1 absorber. A sample of events with muons identified by the counter C was used to measure the penetration (punch through) probability of the accompanying hadrons as a function of the Z position of the vertex and as function of the energy of the hadron shower.

The calculated geometrical acceptance of SC4 was checked by comparing the muon angular distribution corrected using the actual vertex positions and assuming azimuthal symmetry, with that expected from the neutrino spectrum and interaction dynamics. Good agreement was found out to the maximum detected angle of 500 mrad. Only 4% of muons are predicted to lie at angles greater than 500 mrad.

The ratio of muonless events to events with muons is obtained from the formula

$$R = \frac{(\varepsilon_\mu + \varepsilon_p - \varepsilon_\mu \varepsilon_p)(1 + R_m) - 1}{1 - \varepsilon_p(1 + R_m)}$$

where R_m is the measured ratio of events without and with a count in a given muon identifier, ε_μ is the muon detection efficiency and ε_p is the punch through probability.

(a) Experiment 2[2]

This experiment was carried out using 300 GeV protons on an aluminium target and the secondary particles were focussed by a single magnetic horn to provide a beam enriched in autineutrinos. The ratio, α, of the negative muon rate to the total muon rate was measured to be $\alpha = 0.63 \pm 0.11$. The ratio R was measured and no dependence on the position of the vertex or hadron energy was observed and also the data using muon identifiers μ_1 (B or SC4), μ_1' (SC4) and μ_2 (C) were consistent. The results integrated over position and hadron energy yield

$$R = 0.20 \pm 0.05$$

(b) Muonless event rates for inelastic ν and $\bar{\nu}$ interactions

A study[3] was made of four samples of ν and $\bar{\nu}$ interactions obtained using the detector described above and analysed with those methods. Each sample was characterized by a different value of α. For each sample R is related to R^{ν} and $R^{\bar{\nu}}$ by

$$R = \alpha R^{\nu} + (1 - \alpha) R^{\bar{\nu}}$$

Two data samples were obtained by dividing the data in the enriched $\bar{\nu}$ beam into two subsamples with different values of α. This was possible because the magnetic field of the horn was pulsed for a shorter period than the duration of the beam spill. Two other data samples were obtained by using essentially pure beams of neutrinos and autineutrinos (α = 0.98 and α = 0.12). These beams were produced by sign-selection of the charged hadron secondaries.

The analysis of the resulting four data sets is summarized in Table 1. After correction for a small contamination due to ν_e induced events a maximum likelihood fit to the four data sets yields

$$R^{\nu} = 0.11 \pm 0.05 \qquad R^{\bar{\nu}} = 0.32 \pm 0.09$$

Events with two muon candidates

Two events have been observed in which there is an apparent simultaneous production of two penetrating particles of opposite sign (muons). They are induced by ν (or $\bar{\nu}$) of energy greater than 150 GeV, have a considerable hadronic inelasticity and produce a very massive μ-hadron system.

The total numbers of events observed are given in Table 2. The triggering requirements were: either at least 3 GeV deposited in the calorimeter or at least one track through the muon spectrometer.

The following scanning criteria were applied

(i) the events must originate in the liquid

(ii) two or more tracks must traverse at least the first of the 1.25 m thick iron blocks of the muon detector.

Table 1

Summary of data for the four neutrino beam configurations.

Data Sample		Number of events	Muon Detection Efficiency			α	R
			μ_1	μ_2'	μ_3		
Mixed Beam	Horn Off	255	.86	.77	.74	0.74 ± 0.06	0.18 ± 0.05
	Horn On	283	.89	.81	.80	0.45 ± 0.06	0.22 ± 0.05
Sign-selected $(\pi,K)^-$		100	.93	.87	.83	0.12 ± 0.05	0.34 ± 0.12
Sign-selected $(\pi,K)^+$		188	.93	.87	.83	0.98 ± 0.01	0.13 ± 0.06

15 events survived the scanning criteria.

12 of these are rejected immediately since

- 5 do not form a vertex i.e. separation > 2 m
- 2 clearly extrapolate outside the volume
- 1 muon enters from the front
- 4 muons enter from the sides (cosmics)

2 events satisfy the timing and spatial requirements. In addition there is one event in which the two muon tracks do not extrapolate to a common vertex i.e. separation $\sim$ 1 m.

The characteristics of the two $(\mu^+\mu^-)$ events are given in Table 3.

In Fig. 2 the events observed at 400 GeV are displayed in terms of M_X and total energy where

$$\nu_\mu + \text{nucleon} \rightarrow \mu^- + X$$

If we divide the physical region into quadrants I to IV by boundaries at M_X = 7.5 GeV/c^2 and E_ν = 130 GeV, then the two candidates fall in quadrant IV.

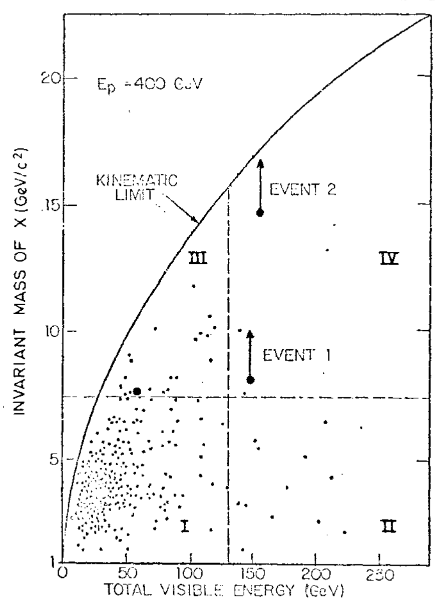

Fig. 2 Distribution of events of the type $\nu_\mu + N \rightarrow \mu^- + X$ as a function of mass (X) and total visible energy. Events involving $\mu^+\mu^-$ production are expected to lie in quadrant IV.

Background events could arise from the following sources

(a) Accidental time and space superposition of two independent ν and $\bar{\nu}$ events

(i) the vertex must be within the same block and within the spatial resolution. Probability $P_1 \sim 10^{-3}$

(ii) the timing must coincide within 150 nsec $P_2 \sim 10^{-3}$

(iii) the kinematic combination of $(\mu^+\mu^-)$ must fall in quadrant IV $P_3 \sim 2.5 \times 10^{-2}$.

Therefore the expected background is

$P_1 \times P_2 \times P_3 \times N_{events} = 2.5 \times 10^{-5}$ event.

(b) Accidental time and space superposition of a $\nu(\bar{\nu})$ interaction and of a $\mu^+(\mu^-)$ track from outside the detector

Probabilities P_1, P_2 and P_3 are as above except that there are 5 times more muons entering than produced in the calorimeter. However the veto efficiency is $\sim$90%. Hence the expected background is $\leqslant 10^{-4}$ event.

(c) A normal $\nu(\bar{\nu})$ event followed by a decay into a muon of a component of the hadron shower

This background was estimated by direct measurements of the π-μ decay probability with π^- of 15,25,35, 50,75,100,125 and 150 GeV in the calorimeter.

The backgrounds in the various quadrants were estimated to be:

- I - 0.5 event
- II - 0.075 event
- III - 0.05 event
- IV - 0.012 event

The two observed events in quadrant IV have thus a small probability to be background.

References

1. A. Benvenuti et al., Phys. Rev. Lett 32(1974) 800.
2. B. Aubert et al., Phys. Rev. Lett 32(1974) 1454.
3. B. Aubert et al., Phys. Rev. Lett 32(1974) 1457.

Table 2

Summary of events observed

E_p	Events	Events E_ν>130 GeV	$\mu^+\mu^-$
300	477	14 (μ^-) 6 (μ^+)	0
400	324	17 (μ^-)	2
TOTALS	801	37	2

Table 3

KINEMATICS OF THE $\mu^+\mu^-$ EVENTS

		Event 1	Event 2	
Run Number		412	415	
Frame Number		253659	254784	
Negative Muon Track				
(a) Momentum	P_{μ^-}	107	36	GeV/c
(b) Angle respect ν-beam	θ_{μ^-}	29	33	mrad
(c) Total number of nuclear collision lengths traversed		58	61	
Positive Muon Track				
(a) Momentum	P_{μ^+}	16.7	13.9	GeV/c
(b) Angle respect to ν-beam	θ_{μ^+}	55	45	mrad
(c) Total number of nuclear collision lengths traversed		58	61	
Hadronic Cascade				
(a) Total energy E_h	E_h	23.7	104.7	GeV
(b) Energy fraction continued inside calorimeter		0.93	0.89	
Total Visible Energy	$P_{\mu+} + P_{\mu-} + E_h$	147	155	GeV
Dimuon Invariant Mass	$M_{\mu\mu}$	3.1	1.0	GeV/c^2
Invariant Mass of (μ^+h) System	$M_{\mu h}$	>7.9	>14.7	GeV/c^2