A search has been carried out for a lepton of the type $Y^+$ as required by some gauge theories. This lepton could be expected to have a decay mode $Y^+ \rightarrow \nu + \bar{\nu} + \nu + \bar{\nu}$, with a branching ratio of approximately 30%. During the experiment 1522 events were found with a $\nu$ and 8 events with a $\bar{\nu}$. Possible sources of background are wrong sign determination in the muon spectrometer (1 event) and antineutrino contamination in the beam (10±5 events). However the antineutrino events would have different characteristics, i.e. would occur mainly at low $y = v/E$. Rejecting events with $y < 0.5$ removes all candidates whereas true $Y^+$ production should only be halved. The expected production rate depends upon the mass of the $Y^+$ and also on the high energy limit of

$$\mathcal{K} = \frac{dN_{hadrons}}{dE} \cdot \frac{dN_{hadrons}}{dE}$$

The following 90% confidence mass limits are obtained

$$\mathcal{K} = 2, \left| G_Y \right|^2 = \left| G_Y \right|^2 \quad M_Y > 8.4 \text{ GeV/c}^2$$

$$\mathcal{K} = 10, \left| G_Y \right|^2 = \left| G_Y \right|^2 \quad M_Y > 7.2 \text{ GeV/c}^2$$

or alternatively if

$$M_Y = 1 \text{ GeV/c}^2 \quad \left| G_Y \right|^2 < 0.2 \left| G_Y \right|^2$$

Theoretical and, more recently, experimental indications of the existence of neutral currents in addition to the usual charged currents of the weak interaction have led to a search carried out in the Caltech-FNAL neutrino detector for the inclusive reactions

$$\nu + N \rightarrow \nu + \bar{\nu} + \text{hadrons}$$

$$\bar{\nu} + N \rightarrow \nu + \bar{\nu} + \text{hadrons}$$

Evidence is presented for the occurrence of such events in a run during February, 1974 at the National Accelerator Lab.

A neutral current search with the Caltech apparatus differs in some ways from the detection of charged current events. Charged current interactions produce a muon which is identified by its penetration through the steel target, as tracked by spark chambers and scintillation counters. (These counters also measure the hadron energy by calorimetry for either type of interaction). A neutral current event, on the other hand, is characterized by observation of a hadron shower only, which is contained, and traverses fewer than 13 counters (135 cm of steel).

The experiment used the primary 300 GeV proton beam with fast-spill extraction (to reduce cosmic ray events). The narrow band beam at FNAL was employed for this search. The secondary hadron momentum was set to 140 GeV, so that decays of pions and kaons in the decay pipe gave neutrinos into the apparatus in energy bands centered at $<E_{\nu}> = 45$ GeV and 130 GeV, respectively. The contribution of neutrinos from
Decays upstream of the decay pipe (wide band) was measured separately by closing a collimator slit located just upstream of the decay pipe entrance. Events were recorded whenever the energy deposition corresponded to more than a 3 GeV hadronic shower. The principal quantities measured for all events (CC or NC) are the vertex position of the hadron shower, hadron shower energy, and the penetration of the longest charged particle. (For charged current events with a visible muon, the muon production angle is also measured). In an attempt at event selection unbiased in the presence or absence of a final state muon, the following criteria were defined: (1) the vertex of the interaction must be at least 12.7 cm from the sides of the target and at least 81.3 cm from the upstream end; (2) the two chambers immediately downstream of the vertex must spark; (3) at least two consecutive counters must have pulse heights greater than or equal to a minimum ionizing signal; (4) hadron energy of at least 6 GeV required in the calorimeter. These criteria select events that consist almost entirely of beam associated, neutrino-induced events. Small contaminations from cosmic rays (2.1% for $\bar{\nu}$, 0.3% for $\nu$) have been subtracted from all distributions. Neutral and charged current events are distinguished by penetration ($p$). Counter tags indicate those counters which contained a pulse height greater than or equal to minimum-ionizing. Each counter tagged corresponds to a penetration of 10 cms of steel.

Figure 1 shows the distribution in penetration, $p$, for the $\bar{\nu}$ events in this experiment. The smooth curve corresponds to the expected distribution for charged current events

$$\bar{\nu} + N \rightarrow \mu^+ + \text{hadrons}$$

normalized to the events with $p > 13$ counters. This curve assumes the usual differential cross-section for charged current interactions, with negligible anti-quark component, consistent with previous analyses of charged current data. The shape of this curve for $p < 13$ is insensitive to this assumption. Even for anti-quark component as high as 20% (inconsistent with existing data), the expected number of charged current events with $p < 13$ would change by less than 30%. The data with $p < 13$ figure 1 is about 400% greater than the expected charged current background.

Figure 2 shows the penetration distribution for $\nu$ events. The charged current contribution, shown as the smooth curve, is again insensitive to detailed assumptions of distribution shape. Only a perverse
anomaly in the distribution of muon angle could produce a sharp peak at small penetration from charged current events. However, if this were the case the energy transmitted to the hadrons would necessarily be large. This follows from a simple kinematic argument. The relationship between muon angle and inelasticity $\gamma = E_{\text{had}}/E_{\nu}$ is

$$4 \sin^2 \frac{\theta}{2} = \frac{2M}{E_{\nu}} \frac{\sin \gamma}{1-\gamma}$$

so that $\theta$ becomes large, the penetration $p$ becomes small, as $y \to 1$. For the data of figure 3, this corresponds to $E_{\text{had}} \sim 40 \text{ GeV}$. This is illustrated by the distributions in $E_{\text{had}}$ for charged current events with moderate penetration ($18 < p < 26$) shown in figure 3a. This distribution peaks at $E_{\text{had}} \sim 20 \text{ GeV}$, about half of the pion neutrino energy. But the events with even smaller penetration ($p < 13$), shown in figure 3b, do not have their major contribution at high energy, but at substantially lower energy. They cannot be due to charged current interactions of pion neutrinos. Indeed figure 3b illustrates dramatically that unobserved energy is transported out of the steel apparatus without interaction.

It is concluded in this preliminary report that neutral current phenomena indeed exist in interaction of both neutrinos and anti-neutrinos. The level of the effect relative to the charged current cross-section is still under analysis. The raw ratios are $R_{\nu}^{\text{raw}} = .33$ and $R_{\bar{\nu}}^{\text{raw}} = .22$. It is expected that the real numbers are within a factor of two of these raw ratios.

There are a number of effects which must be understood and measured before final cross-sections can be quoted:

1. Backgrounds from $\nu_e$ events and from the lower-energy broad-band spectrum need to be more precisely calculated and/or measured and subtracted from the data.

2. The inelasticity distribution of neutral current events must be understood in order to extrapolate to the very low $y$ region ($y \leq .12$); without any knowledge of the neutral current $y$-distribution, this extrapolation introduces an uncertainty of $\% \pm 15-20\%$.

Though some of these questions can be dealt with from this present data, more precise numbers will require separate measurements.

---

**Fig. 3a** Distribution in $E_{\text{had}}$ for charged current events with moderate penetration.

**Fig. 3b** Distribution in $E_{\text{had}}$ for events with small penetration, illustrating that unobserved energy is transported out of the steel apparatus.
Further Investigation on the Events Without Muons in the Gargamelle Neutrino Experiment


Presented by A Pullia

Positive evidence of neutrino-like events, without charged leptons in the final state has been previously reported.\(^1\),\(^2\) Here we give further positive evidence based on the distinction of quantities derived directly from the observed events inside the chamber without regarding the information from the external sources of background. Our understanding of the background has benefited from an independent study of the behaviour of protons and neutrons observed in Gargamelle filled with Freon; this information was obtained with protons of several energies, from 4 to 19 GeV. This analysis confirms our previous study.

The selection and classification of events were defined in the previous papers.\(^1\),\(^2\) Three types of events were considered:

- CC events consist of one possible \(\nu\) in the final state and an identified hadronic shower with an energy \(E_h > 1\) GeV.

- NC events consist of only hadrons identified as before and of energy greater than 1 GeV.

- AS events consist of neutral stars with the same characteristics for hadrons as before and originated from a neutrino interaction inside the chamber.

A fourth category is now considered:

- NS events consist of neutron stars from a proton beam sent into Gargamelle. They were selected with the same criteria for the identification of hadrons and for the energy cut.

The number of events used for the present analysis are reported in Table I.

<table>
<thead>
<tr>
<th></th>
<th>events</th>
<th>films</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>218</td>
<td>60</td>
</tr>
<tr>
<td>NC</td>
<td>189</td>
<td>209</td>
</tr>
<tr>
<td>AS</td>
<td>42</td>
<td>268</td>
</tr>
<tr>
<td>NS</td>
<td>78</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Ratio of neutral current to charged current events along the radial co-ordinate, for \(\nu\) beam (consistent with a constant value).

Fig. 2 Ratio of neutral current to charged current events along the beam axis, for \(\nu\) beam (consistent with a constant value).
In Fig. 1 and 2 are reported the ratio of NC/CC events along the beam axis (x) and along the radial coordinate (R) for ν. Both ratios are consistent with a constant and do not show any attenuation inside the chamber which corresponds along x to ~5 interaction lengths for neutrons.

The comparison between NC, CC and neutrons can be done in a more quantitative way using a likelihood method to deduce the respective apparent interaction lengths. For NC and CC we have taken the direction of the total visible momentum of the hadronic part of the event, as the best estimation of the line of flight of the incident particle.

The results for NC and CC are the following:

\[
\frac{1}{\lambda}_{NC} = 0.16 \pm 0.12 \text{ m}^{-1} \quad \quad \frac{1}{\lambda}_{CC} = 0.39 \pm 0.21 \text{ m}^{-1}
\]

\[
\frac{1}{\lambda}_{NC} = 0.15 \pm 0.10 \text{ m}^{-1} \quad \quad \frac{1}{\lambda}_{CC} = 0.15 \pm 0.14 \text{ m}^{-1}
\]

The values for NC and CC events are in agreement.

These values can then be compared with those characteristics of neutrons. A first information about neutrons comes from the behaviour of those generated in the proton beam experiment. A second information can be gained from the proton interactions themselves, since by charge symmetry they are expected to behave quite similarly to the neutrons in this liquid which has about an equal content of protons and neutrons.

Fig. 3 shows that these two informations give similar results. The mean value obtained is $\frac{1}{\lambda} = 1.4 \text{ m}^{-1}$, in substantial disagreement with the corresponding value for NC events.

To give an estimation of the neutron contamination in NC events, we consider the distribution of events in the following variable $v = (1 - \exp(-\ell/\lambda))/(1 - \exp(-L/\lambda))$ where $\ell, L$ are respectively the apparent flight path and the potential path. $\lambda$ is the interaction length of neutrons. The expected distribution $T(n)$ for a pure neutron beam is flat.

Assuming that NC events are due to the combination of a fraction ($x$) of true neutrino events ($v$) and a fraction ($1-x$) of neutrons ($n$) the following relation is then expected between the distribution functions $T$:

\[
T(\text{NC}) = (1-x) T(n) + x T(v)
\]

The fraction of true neutrino events was fitted to the actual NC distribution and the results are:

\[
x = 0.75 \pm 0.12 \quad \text{for } \lambda = 100 \text{ cm and}
\]
\[
x = 0.85 \pm 0.08 \quad \text{for } \lambda = 70 \text{ cm}
\]

These independent estimations of background are in agreement with that obtained from the previous results obtained with the Monte Carlo methods.

Another possibility to discriminate $\nu$ from neutrons in the NC events is to compare the behaviour of the $\pi^+$ production of the NC-events with that of neutrons.

We choose as a parameter to compare NC events with recognized neutrons (NS and AS) the ratio

\[
r = \frac{\pi^+}{(\pi^- + \pi^0 + \pi^0 + n^+)}
\]

$n^+$ stands for all positive interacting particles in which the proton hypothesis is not excluded. Since AS and NS events have different energy distributions it is necessary to compare their $r$-values at a fixed visible energy.
This is done in Table II. The r-values are compatible for AS and NS events and can be combined. The r-values for NC events are also shown.

<table>
<thead>
<tr>
<th>ΔE</th>
<th>r (AS)</th>
<th>r (NS)</th>
<th>rcombined</th>
<th>rNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 GeV</td>
<td>0.24 ± 0.08</td>
<td>0.38 ± 0.12</td>
<td>0.30 ± 0.07</td>
<td>0.75 ± 0.09</td>
</tr>
<tr>
<td>2-3 GeV</td>
<td>0.10 ± 0.07</td>
<td>0.23 ± 0.09</td>
<td>0.18 ± 0.06</td>
<td>0.53 ± 0.11</td>
</tr>
<tr>
<td>3-5 GeV</td>
<td>0.20 ± 0.20</td>
<td>0.31 ± 0.10</td>
<td>0.30 ± 0.08</td>
<td>0.37 ± 0.08</td>
</tr>
<tr>
<td>5-7 GeV</td>
<td></td>
<td>0.31 ± 0.16</td>
<td>0.31 ± 0.16</td>
<td>0.48 ± 0.16</td>
</tr>
</tbody>
</table>

It seems clear that NC events have a different behaviour than neutrons; the χ² for the two distributions to be compatible is 26.1/4 d.f.; the corresponding probability that the distributions come from the same physical phenomenon is less than 10⁻⁴.

Following the same procedure as in our previous study, we obtain 189 NC events. A reference sample of films provides 218 CC events. The relative ν fluxes of these two samples is used in order to renormalize the ratio NC/CC. The NC sample is corrected for the background estimated from the Monte Carlo, 19 ± 10 events. The CC sample is corrected for a small contamination of 6 unidentified NC events. The final result is

\[ R_ν = 0.217 ± 0.026 \]

Using the evaluations for \( R_ν \) by C. Albright \(^3\) and L. Sehgal \(^4\), it is possible to give a value for the Weinberg parameter \( \sin^2 \theta_W \). Without any correction this value turns out to be 0.40. A correction was applied in order to take into account the selection criteria as well as the energy cut-off, assuming the differential distributions in \( y \) given by these authors. The correction is indeed found to be very small and the final value is:

\[ \left( \sin^2 \theta_W \right)_ν = 0.39 ± 0.05 \]

The same procedure may be applied to our previous result on \( \tilde{R}_ν = (\text{NC}/\text{CC})_ν \) = 0.43 ± 0.12. The correction is more important in that case. The uncorrected value of \( \sin^2 \theta_W \) is 0.44 and the corrected one is 0.26. On the other hand, the experimental error is higher than in the neutrino run.

The final value is

\[ \left( \sin^2 \theta_W \right)_ν = 0.26 ± 0.06 \]

in agreement with the more precise value obtained from \( v \).

It is interesting to see if the study of the observed distribution of the NC events in the hadronic energy can give indications in accordance with the \( \sin^2 \theta_W \) value extracted from the rate \( R_ν \). In order to avoid biases as much as possible, we use the CC events as a starting sample. Then it is possible to compute the distribution in the hadronic energy \( E_H \) for NC event depending upon the value of \( \sin^2 \theta_W \). According to the analysis it turned out that \( \sin^2 \theta_W = 0 \) cannot be excluded by the data. With the theoretical models already used \( ^3,^4 \):

\[ \sin^2 \theta_W < 0.44 \quad \text{68% confidence limit.} \]

We conclude that the \( R_ν \) ratio, the \( \tilde{R}_ν \) ratio and the hadronic energy distributions of (NC) ν events consistent in the Albright \( ^3 \) and Sehgal \( ^4 \) model with one single value \( \sin^2 \theta_W = 0.39 ± 0.05 \).

References
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 \( \nu \) and \( \overline{\nu} \).

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 \((\mu_1)\) 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 \((\mu_2)\).

To use the counter B or SC4 as a muon identifier it is necessary to measure the probability \( c_p \) that hadrons penetrate the \( \mu_1 \) 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

\[
R = \frac{(e_\mu + e_\overline{\mu} - e_\mu^c)(1 + R) - 1}{1 - c_p(1 + R_m)}
\]

where \( R_m \) is the measured ratio of events without and with a count in a given muon identifier, \( c_\mu^c \) is the muon detection efficiency and \( c_p \) 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 antineutrinos. The ratio, \( \alpha \), 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

Fig. 1 FNAL apparatus to study neutral current events.
energy was observed and also the data using muon
identifiers $\mu_1$ (B or SC4), $\mu_2$ (SC4) and $\mu_3$ (C) were
consistent. The results integrated over position and
hadron energy yield

$$R = 0.20 \pm 0.05$$

(b) Muonless event rates for inelastic $\nu$ and $\bar{\nu}$
interactions
A study (1) was made of four samples of $\nu$ and $\bar{\nu}$
interactions obtained using the detector described
above and analysed with those methods. Each sample
was characterized by a different value of $\alpha$. For
each sample $R$ is related to $R^\nu$ 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 $\nu^-$ beam into two subsamples with
different values of $\alpha$. 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 antineutrinos
($\alpha = 0.98$ and $\alpha = 0.12$). 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 $\nu_e$ induced events a maximum
likelihood fit to the four data sets yields

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

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 $\nu$ (or $\bar{\nu}$) of energy greater than 150 GeV,
have a considerable hadronic inelasticity and
produce a very massive $\nu$-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>
<thead>
<tr>
<th>Data Sample</th>
<th>Number of events</th>
<th>Muon Detection Efficiency</th>
<th>$\alpha$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Horn Off</td>
<td>255</td>
<td>0.86</td>
<td>0.77</td>
<td>0.74</td>
</tr>
<tr>
<td>Mixed Horn On</td>
<td>283</td>
<td>0.89</td>
<td>0.81</td>
<td>0.80</td>
</tr>
<tr>
<td>Sign-selected ($\nu$,K$^-$)</td>
<td>100</td>
<td>0.93</td>
<td>0.87</td>
<td>0.93</td>
</tr>
<tr>
<td>Sign-selected ($\bar{\nu}$,K$^+$)</td>
<td>188</td>
<td>0.93</td>
<td>0.87</td>
<td>0.98</td>
</tr>
</tbody>
</table>
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 ~ 1 m. The characteristics of the two \((\nu^+ \nu^-)\) 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

\[\nu^+ + \text{nucleon} + \nu^- + X\]

If we divide the physical region into quadrants I to IV by boundaries at \(M_x = 7.5\) GeV/c\(^2\) and \(E_v = 130\) GeV, then the two candidates fall in quadrant IV. Background events could arise from the following sources

(a) Accidental time and space superposition of two independent \(\nu\) and \(\bar{\nu}\) events
   (i) the vertex must be within the same block and within the spatial resolution. Probability \(P_1 \approx 10^{-3}\)
   (ii) the timing must coincide within 150 nsec \(P_2 \approx 10^{-3}\)
   (iii) the kinematic combination of \((\nu^+ \nu^-)\) must fall in quadrant IV \(P_3 \approx 2.5 \times 10^{-2}\).
   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 \(\nu^+ (\nu^-)\) 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 \(\approx 90\%\). Hence the expected background is \(\approx 10^{-4}\) 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 \(\pi\nu\) decay probability with \(\nu^+\) 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
Table 2
Summary of events observed

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>Events</th>
<th>$E_{\nu}&gt;130$ GeV</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>477</td>
<td>14 ($\mu^-$) 6 ($\mu^+$)</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>324</td>
<td>17 ($\mu^-$)</td>
<td>2</td>
</tr>
<tr>
<td>TOTALS</td>
<td>801</td>
<td>37</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3
KINEMATICS OF THE $\mu^+\mu^-$ EVENTS

<table>
<thead>
<tr>
<th>Event 1</th>
<th>Event 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run Number</td>
<td>412</td>
</tr>
<tr>
<td>Frame Number</td>
<td>253659</td>
</tr>
</tbody>
</table>

Negative Muon Track
(a) Momentum $p^-_{\mu}$ | 107 | 36 | GeV/c |
(b) Angle respect $\nu$-beam $\theta^-_{\mu}$ | 29 | 33 | mrad |
(c) Total number of nuclear collision lengths traversed | 58 | 61 |

Positive Muon Track
(a) Momentum $p^+_{\mu}$ | 16.7 | 13.9 | GeV/c |
(b) Angle respect to $\nu$-beam $\theta^+_{\mu}$ | 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 ($\mu^+ h$) System | $M_{\mu h}$ | >7.9 | >14.7 | GeV/c$^2$ |
The amplitude of the weak neutral currents in neutrino interactions can be estimated via the study of neutrino scattering on electrons.

\[ \nu + e^- \rightarrow e^- + \nu \]  
\[ \bar{\nu} + e^- \rightarrow e^- + \bar{\nu} \]

I shall present today a status report of the search which is currently being made in Gargamelle for the reaction (2) which, as reaction (1), is forbidden at the first order in the V-A theory.

Last year, Hasert et al. reported a candidate for this reaction observed during the double scan of two lots of pictures taken with Gargamelle filled with CF$_3$Br and exposed at the CERN PS to beams of neutrinos (375,000 pictures) and antineutrinos (360,000 pictures). The event had been found in the $\bar{\nu}$ pictures where the background was estimated to be 0.03 ± 0.02 event.

Since that work, the Gargamelle Collaboration has now achieved the double scan of an additional lot of $\bar{\nu}$ pictures corresponding to an increase in statistics of about a factor 3 compared to the previous $\bar{\nu}$ sample. Most of these pictures were taken using the facilities offered by the installation of the new CERN PS injector. The experiment is still in progress and the results I am presenting concern the whole $\bar{\nu}$ data analyzed up to now, including those of Hasert et al. (1)

The characteristic signature for reaction (4) consists of an isolated electron track originating in the liquid at a small angle $\theta_e$ with respect to the antineutrino beam.

In the Gargamelle experiment a cut-off on $E_e$ is imposed at 300 MeV to assure a reasonable scanning efficiency and to remove a possible background due to low energy $\gamma$ rays. As a result of kinematics the angle $\theta_e$ should be less than about 5°.

In a heavy liquid bubble chamber, the identification of electron tracks is almost straightforward from their characteristic spiral and the observation of bremsstrahlung effects. However, some experimental difficulties remain regarding (i) the determination of the sign of the electron charge above a given energy and (ii) the separation of energetic $\gamma$ rays (zero opening angle) from single electrons. Table I summarizes the characteristics of all isolated electrons, positrons and $\gamma$ rays of energy greater than 300 MeV and angle less than 5° with respect to the neutrino beam detected after double scan in the Gargamelle experiment. It is seen that two unambiguously identified isolated electrons have been observed.

Different reactions induced by neutral particles which can simulate the signal have been carefully investigated by Hasert et al. (1). It was shown by these authors that the major source of background was due to the quasi elastic scattering of electronic neutrinos on nucleons

\[ \nu_e + n \rightarrow e^- + p \]  

leading in the final state to a single electron emitted at small angle ($\theta_e < 5^\circ$), the proton being either of too low energy to be observed or remaining trapped in the parent nucleus without visible evaporation products.
The $\nu_e$ contamination present in the CERN $\nu_e$ beam is known to be small (<1%), preventing a meaningful study of the phenomenological characteristics of the $\nu_e$-nucleon interactions to be done. To estimate the background due to reaction (3), Hasert et al.\(^{(5)}\) studied the more frequent reaction

$$\nu_e + n \rightarrow \nu^- + p \quad (4)$$

which at high energy is kinematically similar to reaction (3). They concluded that the probability of occurrence of the background configuration was 1.3 ± 0.7%. Using this value and the known $\nu_e$ flux in the $\nu_e$ beam, the number of background events due to reaction (5) is estimated to be 0.12 ± 0.08. It should be stressed that no upper limit was put on the recoiling electron energy although it is expected that the electrons from the background reaction (3) should be on average more energetic than those from the reaction sought (2).

From Table I it is seen that at most 3 isolated electron-positron pairs of energy greater than 300 MeV and making an angle less than 5° with respect to the beam direction have been observed. Using the appropriate ratio of Compton to pair production cross sections and the known energy distribution between the electron and the positron of a pair, $\gamma$ rays could contribute at most 0.06 ± 0.03 background events.

As a result, the maximum contribution of the background is found to be 0.18 ± 0.12 events. This is to be compared with two unambiguous isolated electrons observed in the experiment. The probability that these two events could be due to the background is thus about 1.5%.

Inspection of Table I reveals that there exist two ambiguous isolated electrons. The $e^\pm$ candidate is of high energy as well as the three positrons which can be attributed to reaction

$$\nu_e + p \rightarrow e^+ + n \quad (5)$$

It is known that the sign of the charge of an electron (positron) cannot be determined in about 50% of the cases at energies above 2 GeV\(^{(2)}\). The one $e^+$

<table>
<thead>
<tr>
<th>Event no</th>
<th>Type</th>
<th>Position in the chamber</th>
<th>Angle (degrees)</th>
<th>E (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$e^-$</td>
<td>1647, 89, 139</td>
<td>1.4 ± 1.6</td>
<td>385 ± 100</td>
</tr>
<tr>
<td>2</td>
<td>$e^-$</td>
<td>374, 157, -358</td>
<td>2 ± 2</td>
<td>500 ± 120</td>
</tr>
<tr>
<td>3</td>
<td>$e^-$</td>
<td>-1090, -140, -260</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>$\gamma$</td>
<td>1723, -48, -148</td>
<td>4.8</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>$\gamma$</td>
<td>-1148, 283, -561</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>6</td>
<td>$e^+$</td>
<td>-840, -120, 400</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>7</td>
<td>$e^+$</td>
<td>-316, -43, 533</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>8</td>
<td>$e^+$</td>
<td>-580, -490, 130</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>9</td>
<td>$e^+$</td>
<td>1458, 328, 280</td>
<td>5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
candidate can thus be attributed to process (5). It is worthwhile to mention that the number of isolated $\gamma$ satisfying the scanning criteria to be expected from this reaction in the present experiment is in fair agreement with the observations. The estimate of that number was done from the observed number of events of the type $\nu_e + p \rightarrow \mu^+ (\theta_\mu < 5^\circ) + $ undetected neutron in a sample of the film, and the $\nu_e/\gamma$ flux ratio.

At this stage of the affair where we have still to prove the existence of purely leptonic neutral currents it is more conservative to consider the $e^-\gamma$ event as a $\gamma$ ray and to correct the observed signal (two unambiguous $e^-$) taking account of the probability for an electron to appear as a $\gamma$ ray.

From the cross section calculated by 't Hooft (3) knowing the $\nu_\mu$ flux, it is possible to estimate the expected number of events as a function of $\sin^2 \theta_\mu$. Taking account of (i) the experimental cut on the electron energy (typically, the fraction of events which survive the cut lies between 60 to 85%, assuming an isotropic distribution of the scattering angle in the CMS), (ii) the scanning efficiency (> 90%) (iii) the background, it is found that $\sin^2 \theta_\mu < 0.45$ at a 90% confidence level.

The limits on the cross section for process (2) are $0.03 \times 10^{-41} < \sigma < 0.29 \times 10^{-41} \text{ cm}^2/\text{el}$ at a 90% C.L.

REFERENCES

RESULTS FROM THE ARGONNE 12-FOOT BUBBLE CHAMBER EXPERIMENT
Argonne, Concordia, Purdue Collaboration
Presented by P. Schreiner

There have been to date three exposures - one with a hydrogen filling and two with deuterium; a total of 700,000 pictures has been analysed, which corresponds to $0.9 \times 10^{18}$ protons on the production target.

Reactions $\nu_p + n \rightarrow \mu^+ (1), \nu_p \rightarrow \gamma (2)$

The signal for reaction (1) is a single $\pi^+$ meson originating in the chamber fiducial volume. Tracks were identified by (i) A clear $\pi^+\rightarrow e^+\gamma$ decay on a stopped track (ii) A kinematically fitted $\pi^+p$ elastic scatter (iii) Energy loss on low momentum tracks.

The following selections were applied to 18 candidates:
- $P < 400$ MeV/c. This was to ensure good discrimination by method (iii).
- The dip angle $\lambda < 0$. Incoming neutrons can simulate neutral current events in the reaction $np + \pi^-\pi^+\mu^+\mu^-$.
- The charge symmetric reaction $np + \pi^-\pi^+\mu^-$ is observed and it is found that 90% of the neutrons and $\pi^-$ are directed downwards ($\lambda > 0$) indicating that the neutrons are entering by the weakly shielded top of the chamber.
- The event must be >20cms away from any cosmic ray track. This was to remove background from the reaction $\nu_p + p \rightarrow \pi^-$ with the $\gamma$ produced by a cosmic ray.

The effects of the selection criteria together with the remaining backgrounds are shown in Table 1.
### Table I

**Event and Background Summary**

<table>
<thead>
<tr>
<th>Event Types</th>
<th>$H_2$</th>
<th>$D_2$</th>
<th>Total</th>
<th>After 20 cm Cosmic Cut</th>
<th>After $\pi^+$ Dip Angle Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$ Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decaying $\pi^+$</td>
<td>2</td>
<td>8</td>
<td>10</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Scattered $\pi^+$</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Leaving $\pi^+$</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$1$-Prong + $\gamma$ Events</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total Events</td>
<td>26</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Background Types

- Neutron-Induced: 0.55 ± 0.55
- Photo-Produced: 0.33 ± 0.10
- $\pi^-p \rightarrow \pi^-n$: 0.04 ± 0.04
- Accidental $\gamma$ Pointing: 0.11 ± 0.11
- Total Background: 2.49 ± 0.73

*For the $H_2$ exposure, all three $\pi^+$ modes have been analyzed; for the $D_2$ exposure, somewhat different fractions of the film have been processed for the three modes.*

### Table II

**Summary of Background, $vp \rightarrow vp$ and $\nu n \rightarrow \mu^-n$ Events**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$q^2 &gt; 0.43\text{GeV}^2$</th>
<th>Further Cut on $\phi$ Between 216 and 324°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$np \rightarrow np\pi^0$</td>
<td>0.73 ± 0.73</td>
<td>0.27 ± 0.27</td>
</tr>
<tr>
<td>$np \rightarrow nn\pi^0$</td>
<td>0.28 ± 0.28</td>
<td>0.09 ± 0.09</td>
</tr>
<tr>
<td>$\bar{\nu}p \rightarrow \mu^-\pi^+$</td>
<td>1.14 ± 0.57</td>
<td>0.34 ± 0.17</td>
</tr>
<tr>
<td>$\nu p \rightarrow v\pi^+$</td>
<td>5.13 ± 2.72</td>
<td>1.54 ± 0.82</td>
</tr>
<tr>
<td>$\nu p \rightarrow v\pi^0$</td>
<td>0.14 ± 0.07</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>$\pi^-p \rightarrow$ neutral</td>
<td>0.52 ± 0.26</td>
<td>0.31 ± 0.22</td>
</tr>
<tr>
<td>$\nu p \rightarrow ps^0/n\pi^+$</td>
<td>0.02 ± 0.02</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Subtotal</td>
<td>7.96 ± 2.90</td>
<td>2.60 ± 0.91</td>
</tr>
<tr>
<td>$np \rightarrow np$</td>
<td>77.07 ± 7.60</td>
<td>2.31 ± 2.26</td>
</tr>
<tr>
<td>Total Estimated Background</td>
<td>85.03 ± 8.13</td>
<td>4.91 ± 2.44</td>
</tr>
</tbody>
</table>

**TotalObserved Events**: 82

- $vp \rightarrow vp\text{Signal}$ | -3.03 ± 8.13 | -0.91 ± 2.44 |
- $\bar{\nu}n \rightarrow \mu^-p$ | 37.16 ± 4.13 | 11.15 ± 1.24 |
The signal for reaction (2) is a proton track originating in the fiducial volume with a converted γ-ray (e⁺e⁻ pair) pointing to the origin of the proton track. The following selection criteria were applied to the 13 candidates found:

- The dip and azimuthal angles of the proton were <60°. It was found that 99% of the events νp→π⁺p satisfied this criterion.
- Proton momentum <1 GeV/c. 91% of νp→π⁺p events satisfied this criterion.
- Vertex >20cm from a cosmic ray.

The effects of these selection criteria and the remaining backgrounds are shown in Table 1. In this case the neutron background estimate was based upon the observed number of pp⁻ events and the ratio νp/pp⁻ measured in a separate exposure to a 0.3 GeV/c neutron beam.

Hence the overall result is a total of 14 events with an estimated background of 2.49 ± 0.73. As a statistical fluctuation this has a probability of 1.2 x 10⁻⁵, i.e., a 4.3 standard deviation effect. By applying the same criteria to the ν⁺ and proton from the events νp→π⁺p one measures the neutral to charge current ratios:

$$R_0 = \frac{\sigma(νp→πpν^+)}{\sigma(νp→π^+p)} = 0.17 ± 0.08$$

Using the Salam-Weinberg formulation of a renormalizable gauge theory of weak and electromagnetic interactions, Albright et al. have calculated lower limits to $R_0 + R_+$. Theoretical predictions are also shown. Sakurai has constructed a simple model of neutral currents that is characterized by an isoscalar neutral current. In this model there can be no $\delta^4(1236)$ production in (1) and (2) and therefore the predicted cross-sections are small ($R_0 + R_+ < 3\%$) at ANL energies. This is not supported by the present data.

The reaction νp→p

A scan was made for leaving 1-prongs in the 12-foot chamber; this data sample contains unbiased protons with momentum greater than 550 MeV/c. Of the three film exposures mentioned above, only the last deuterium one was used, since the neutron background is clearly smallest in this exposure. A total of 1131 1-prongs were found. Since the shielding on top of the chamber is known to be weak, it is relevant.
to examine the azimuthal angle of the 1-prongs about the $v$ beam direction. The events show a strong peak at $90^\circ$ corresponding to protons going downwards.

From a Monte Carlo calculation of $np \to np$ using the known $np$ elastic differential cross section as a function of neutron momentum, assuming a neutron flux of the form $P(n) = A P^m$, and taking the directions of the neutrons from the (a) $np \to pp$ fits and/or (b) the proton directions of those 1-prongs greater than 700 MeV/c, one is able to reproduce the observed distribution in azimuthal angle. Using the Monte Carlo as a guide, a selection is made on the azimuthal angle:

$216^\circ < \theta < 324^\circ$. Four events above 700 MeV/c satisfy this angular cut (30% of the entire angular range).

One must next determine the magnitude of the background reactions. Table II gives a summary of the various backgrounds, the basic techniques used to measure them, and the results. Note that (a) one cannot separate fast protons from $n^+$'s, (b) that $vp \to vp^0$ is a large background (1), and (c) the neutron background is manageable once the angular cut is applied.

The experiment does not observe neutral currents and measures a preliminary ratio of

$$\frac{\sigma(vp + vp)}{\sigma(vp + \mu^- \pi^+)} = -0.08 \pm 0.20.$$  

This experiment appears to have the potential to observe $vp + vp$ after obtaining additional low neutron background film.

The Reaction $vn \to vp^-(3)$

This 0-constraint reaction is being searched for in the Argonne deuterium fillings of the 12-foot. To eliminate background from the charged current processes such as $vn \to \nu^- \mu^+$, all candidates for reaction (3) must have a strong interaction secondary scatter on the negative track. To further purify the data sample, some of the selection criteria found useful in the study of reactions (1) and (2) have also been applied to $vp^-$: pion momentum less than 400 MeV/c, proton momentum less than 1000 MeV/c, and the spectator proton less than 300 MeV/c. By using dE/dx energy loss, incoming charged track scatterers were also eliminated.

The preliminary data sample consists of 14 events. While the photo-induced, $\pi^0$, and $K_L^0$ backgrounds are estimated to be negligible, the neutron background from $nn \to np^-n$ is $2 \pm 2$ events (after applying the above-mentioned cuts). So the reaction $vn + vp^-$ appears to exist and to have an appreciable cross section. Fig. 2 displays the energy dependence of the cross section for $\tau^-$ momentum <400 MeV/c and $p$ momentum less than 1000 MeV/c.

The neutral to charge current ratio

$$\frac{\sigma(vn + vp^-)}{\sigma(vp + \mu^- \pi^+)} = 0.18 \pm 0.07$$

is similar to that measured for reaction (1).

Fig. 3(a) shows the $p^-$ effective mass spectrum for reaction (3). There are many events below 1236 MeV, although the $\tau$ and $p$ momentum cuts permit mass values up to 1400 MeV. This surprising result needs to be investigated further. Fig 3(b) shows the histogram of $q^2$; this distribution is quite similar to that of the reaction $vp + \mu^- \pi^+$ and about what one would naively expect.

References

OBSERVATION OF MUOLESS NEUTRINO REACTIONS

Columbia, Illinois, Rockefeller, Brookhaven Collaboration

Presented by W. Lee

We have carried out an experiment in the neutrino beam at the AGS to look for muonless events induced by neutrinos. Such events were first observed by Gargamelle at CERN and subsequently by groups at Fermi National Laboratory and Argonne Laboratory.

The detector consisting of 26 modules of narrow gap aluminium optical spark chambers interspersed with liquid and plastic scintillation counters, was located 150 feet behind the muon shield. An additional shield to decrease the muon background was located 50 feet upstream of the detectors. This allows enough distance between the detectors and shield to differentiate neutrino and neutron induced reactions by time of flight measurement. The pulse height and time of flight were recorded for every hit for all scintillation counters.

The neutrino beam spill consisted of 12 to 13 r.f. bunches with a width of 35 nsec separated by 220 nsec. Fig. 1 shows the time of flight of fast muons.

We have taken $3 \times 10^3$ pulses with an average intensity of $4 \times 10^{12}$ protons on target. Scanning information from 1/6 of the total film was examined and all events with a vertex and an associated shower or interacting track collected. The time of flight spectrum of these events indicates no significant neutron contamination of the sample.

Each track in an event was classified into one of five categories:

1. Clear muon (greater than two interaction lengths)
2. Leaving straight track
3. Stopping straight track
4. Interacting track (kink or shower)
5. Short track

A short track track is a track less than or equal to the maximum length defined for nuclear debris (3.5 in. of aluminium). Where possible, an attempt was made to identify stopping and leaving tracks as protons by examining the pulse height of the counters traversed.

Muonless events (N.C.) were then defined to be events which included track types 4 and 5 only. Charged current (C.C.) events were defined to have track types 1, 4 and 5 only. The total number of charged current events observed was 111. After correction for absorption in the target this number becomes 130. The total number of muonless events observed was 45. Low energy and wide angle muon contamination of this sample is calculated to be 5 events. A 20% change in the energy of the neutrino spectrum brings this to 6 events. We conclude from this that there is a clear neutral current signal.

A simple division of these two numbers does not give $R = NC/CC$ because our target consists of neutrons and protons and hence some of the final states for neutral currents are twice those for charged currents. Furthermore our detection efficiency depends on the final state observed.
We have analyzed the single $\pi^0$ production channels in detail. Protons from NC and CC candidates were studied and the energy and angular correlations of the two samples found to be similar. We have obtained a value of $R$.

$$R = \frac{\sigma (\nu + n \rightarrow \nu + n + \pi^0) + \sigma (\nu + p \rightarrow \nu + p + \pi^0)}{2\sigma (\nu + n \rightarrow \mu^- + p + \pi^0)}$$

After low energy and wide angle muon corrections we have 14 neutral current candidates and 66 charge current events in these channels. Using these numbers, the result is:

$$R = \frac{14}{66 \times 1.6} = 14 \pm 7\%$$

The factor 1.6 is due to nuclear breakup correction. The error includes 3.4% due to statistics, 2% due to low energy and wide angle muon uncertainty and 1.7% due to the efficiency for detecting the neutron final state.

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**OBSERVATION OF SINGLE PION PRODUCTION IN NEUTRINO-LIKE INTERACTIONS WITHOUT A CHARGED LEPTON**

**CERN**

Presented by A Rousset

Results of the 1967 CERN bubble chamber experiment have been published (1) and included an upper limit for single $\pi^+$ production by a neutral current (2). The pictures were re-analysed to find events consistent with the reactions:

1. $\nu_p \rightarrow \nu_n \pi^+$
2. $\nu_p \rightarrow \nu_p p \pi^0$
3. $\nu_n \rightarrow \nu_n \pi^0$  
   (dirty)
4. $\nu_p \rightarrow \nu_p p ^-\pi^+$
5. $\nu_p \rightarrow \nu_p p ^+\pi^-$

where the final state protons and pions were positively identified.

The $\pi^+$ were identified as positive tracks with momenta below 0.7 GeV/c characterised by either its decay ($\pi^+ \rightarrow \mu^+ e^+$), or by an interaction where the range of the particle or its ionisation is not compatible with a proton of the same momentum. The $\pi^0$'s were identified by one $\gamma$-ray converted into an electron pair in the liquid. The $\pi^-$'s were identified as negative interacting particles. The protons were identified by their range, if they stopped, or by the ionisation of the track.

A single $\pi^+$ event was eliminated because it was compatible with cosmic-ray induced photo-production. The other events are not correlated with cosmic rays.

The number of events found to be compatible with reactions (1-5) are given in Table 1. All events were divided between two classes:

(i) "clean" events, in which charge is conserved according to the reaction scheme, and
(ii) "dirty" events, in which an otherwise clean topology is accompanied only by slow stopping protons.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Identified tracks</th>
<th>Events</th>
<th>Clean</th>
<th>Dirty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) $\nu_n \pi^+$</td>
<td>$\pi^+$</td>
<td>3 + 1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>(2) $\nu_p \pi^0$</td>
<td>$\pi^0$</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(3) $\nu_n \pi^0$</td>
<td>$\pi^0$</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(4) $\nu_p \pi^-$</td>
<td>$\pi^-$</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(5) $\mu^- p \pi^+$</td>
<td>$\pi^+$</td>
<td>50</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^-$</td>
<td>77</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^0$ and $p$</td>
<td>37</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>
The reactions (1), (2), (3) and (4) cannot be kinematically constrained and the $\pi^+$, $\pi^0$ or $\pi^-$ could be produced by neutrons in the reactions:

$$np \rightarrow nn^+$ (6)  
$$np \rightarrow np_{n}^0 (7)  
$$nn \rightarrow nn_{T}^0 (8) \text{ (dirty)}  
$$nn \rightarrow np_{\pi}^+ (9)$$

The neutron flux can be estimated by the reaction:

$$np \rightarrow pp^- (10)$$

A search was made for events compatible with this reaction. Only one such event has been found, and it also compatible with the reaction: $\bar{v}p \rightarrow \pi^+ p$. By charge symmetry reactions (6) and (10) have equal cross sections and in this experiment the $\pi^+$ and $\pi^-$ detection efficiencies are approximately equal. The hypothesis that the 9 $\pi^+$ events were produced by reaction (6) and only one event by reaction (10) may therefore be rejected as having a probability smaller than $10^{-2}$.

At low neutron momenta (below 2.5 GeV/c) the cross section for reaction (9) is greater than six times that for reaction (6). Taking account of the relative number of effective proton and neutron targets in propane, the number of $nn^+$ and $np^- \pi^-$ events should be in a ratio of less than 1/3. The 3 $\pi^+$ events and the possible $pp^-\pi^-$ event are the only candidates for reaction (9) in which the $\pi^-$ at least is positively identified. The hypothesis that the 9 $\pi^+$ and the 4 $\pi^-$ events are produced by neutrons can therefore only be retained at a confidence level of less than 2 $10^{-3}$.

In conclusion the 9 $\pi^+$ events are incompatible with the background at a $10^{-3}$ level of probability and these events can be considered as further evidence for the existence of weak neutral currents.

The cross section for pion production by neutral currents may be compared to that of the charged current process (5). The comparison is done using the events compatible with the $\bar{v}p \pi^+$ topology, clean or dirty, applying the same identification criteria as for the $\pi^+$ events.

$$R_+ = \frac{\sigma(np \rightarrow np_{\pi}^+)}{\sigma(np \rightarrow np_{p}^+)} = 8 \pm 1.04$$

Using only the 3 measured clean events, the ratio is

$$R_+ = \frac{\sigma(np \rightarrow np_{\pi}^+)}{\sigma(np \rightarrow np_{p}^+)} = 0.06 \pm 0.04$$

In the $p\pi^+$ events the background contribution is estimated to be approximately one event. Therefore the 3 $p\pi^+$ candidates cannot be taken as a significant signal for neutral current interactions, but an upper limit for the processes (2) and (3) can be given:

$$R_+ = \frac{\sigma(np \rightarrow np_{\pi}^+)}{\sigma(np \rightarrow np_{p}^+)} = 0.07 \pm 0.05$$

The factor 1/3 takes into account the relative number of neutrons and protons in the propane and the probability for an interaction to appear as dirty.

In the case of the 3 $p\pi^-$ events the contribution of the neutron background can be large, and the following upper limit can be given:

$$R_+ = \frac{\sigma(\nu n \rightarrow \nu n_{\pi}^-)}{\sigma(\nu n \rightarrow \nu n_{p}^+)} = 0.06 \pm 0.04$$

References
