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Ratio of Neutral Current to Charged Current Cross Sections for Inclusive Neutrino Interactions in Hydrogen*

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Abstract

The ratio of neutral current to charged current cross sections is determined from a sample of events obtained in an exposure of the Fermilab 15' Hydrogen Bubble Chamber to a high energy, horn-focused neutrino beam. For events with 3 or more prongs and with visible hadron momentum above 10 GeV/c, the ratio is 0.40 ± 0.14. A Monte Carlo calculation assuming the Weinberg-Salam model is used to correct for excluded events, yielding $R_{NC/CC} = 0.48 \pm 0.17$.

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The understanding of weak interactions changed drastically with the discovery of neutral current events in 1973.[1] Since that time there have been other experimental results for ν and $\bar{\nu}$ neutral current interactions at high energy,[2] but always a "heavy" target with approximately equal numbers of neutrons and protons has been used. The study of neutral current (NC) interactions in hydrogen is also important since the interaction rate with a pure proton target can be measured and the details of the final hadronic state may be studied without the complexities introduced by secondary interactions in complex nuclei. This paper describes the determination of $R_{NC/CC}$ = Rate $(\nu + p \rightarrow \nu + X^{+})$/Rate $(\nu + p \rightarrow \mu^{-} + X^{++})$.

The events come from 62,000 pictures obtained using a wide-band neutrino beam incident on the Fermilab 15' Bubble Chamber filled with hydrogen. The neutrino beam was obtained by focusing positive secondaries from interactions of 300 GeV protons in a 25 cm long aluminum target with a single magnetic horn. The typical proton intensity during this exposure was 0.5×10^{13} protons per pulse. The energies of the neutrino events range to over 200 GeV, but the typical neutrino energy is between 20 and 30 GeV.

The event sample used here overlaps greatly with the sample used earlier in the analysis of neutrino charged current (CC) events.[3,4] The CC events were previously analyzed using the Cundy-Burmeister-Myatt Methods[5] to select the muon and estimate the incoming neutrino energy. The energy estimation method tends to fail NC events and therefore acts to separate CC interactions from NC interactions. The present analysis uses a different kinematic criterion and the External Muon Identifier[6] (EMI) to separate NC events.

Events not associated with interactions in the wall of the bubble chamber, reconstructing fully in the geometry program, contained within the fiducial volume (20 m^3), and having a visible momentum in the neutrino direction (ΣP_x^{vis}) greater than 10 GeV/c are used in the final analysis.

To determine the number of charged current events, the Fermilab External Muon Identifier, which is comprised of an array of 24 one-meter square, multiwire proportional chambers mounted directly on the back of the 15' Bubble Chamber, has been used. The positions of all particles emerging from the EMI absorber, which is located inside the bubble chamber vacuum tank, are recorded on tape and are later compared with those found by extrapolating tracks seen in the bubble chamber to the EMI plane assuming that they are muons. The actual number of muons in a sample of tracks in all analyses in this paper is determined statistically.[7] After correcting for the EMI acceptance, which has been determined from a Monte Carlo calculation, 399 ± 18 μ^- and 39 ± 12 μ^+ (from antineutrino charged current events) are estimated to be in the final sample. The uncertainties are the statistical uncertainties from the EMI analysis.

A simple kinematic cut is used to help separate CC events and muonless events. This method is based on the observation that hadrons in neutrino CC interactions have a limited transverse momentum distribution about the total hadron direction.[4] The method is illustrated in Fig. 1 (insert). The "muon" is chosen as the negative non-interacting track with the highest transverse momentum relative to the neutrino direction. The sum of the momenta of the remaining tracks is then used to define the "hadron direction," and the transverse momentum, P_T, of the "muon" relative to this direction is found.

For CC events the muon usually has a large transverse momentum relative to the hadron direction. For NC events, however, the "muon" selected is just one of the hadrons, and its transverse momentum relative to the remaining hadrons will be small.

The distribution of events in P_T^2 is shown in Fig. 1. Also shown is the number of muons in each bin as determined by the EMI. All tracks are used in this analysis, so a wrong kinematic selection of the muon in a CC event does not cause the real muon to be lost. For $P_T \geq 1$ GeV/c, essentially all events are ν CC events. However for $P_T < 1$ GeV/c, there is a large excess of events, exactly where the NC events are expected.

The Monte Carlo predicts that 89% of NC events, 9% of ν CC events, and 87% of $\bar{\nu}$ CC ($\overline{CC}$) events should be retained in the sample with $P_T < 1$ GeV/c. Only the first two efficiencies are used since the $\overline{CC}$ contamination will be detected directly. The first efficiency is very insensitive to the form (assumed x-y distributions) of the NC interaction.

The background contamination from neutron interactions has been estimated from the number of $np \rightarrow pp\pi^-$ interactions seen in the bubble chamber, as described in Ref. 4. The important observation is that most of these events are at very low momentum. By requiring the event sample to have a value or $\Sigma P_x^{vis} > 10$ GeV/c, a clean sample of NC events is obtained. The number of neutron induced background events remaining in the final sample is estimated to be 10 ± 7.

The K_L^o induced background contamination is estimated in a similar fashion from the number of events which kinematically fit $K_L^o p \rightarrow K_S^o p\pi^+\pi^-$. This method predicts a background of 6 ± 3 K_L^o events in our final sample.[9]

Backgrounds arising from ν_e and $\bar{\nu}_e$ interactions are negligible. Background due to $\bar{\nu}$ NC events ($\overline{NC}$) is also quite small. Using a value of 0.4 for the ratio of $\overline{NC}/\overline{CC}$[2] and the measured number of $\overline{CC}$ events and multiplying by the fraction surviving the ΣP_x^{vis} cut, the expected number of events is 5 ± 2. The various backgrounds are summarized in Table I.

In a NC event much of the initial neutrino energy may be carried away by the final state neutrino, leaving the event with a small ΣP_x^{vis}. (Here ΣP_x^{vis} is just the visible momentum of the final state hadrons in the x direction, $\Sigma P_x^{vis\ had}$.) Since the events in our sample must have a ΣP_x^{vis} greater than 10 GeV/c, the acceptance of NC events is much smaller than for CC events. Indeed, our Monte Carlo program estimates that only 9% of CC events are lost, while 64% of NC events are lost by a 10 GeV/c cut in ΣP_x^{vis}.

Rather than comparing the number of NC and CC events directly, it is better to compare the number of NC events detected for a particular ΣP_x^{vis} cut to the number of CC events satisfying the same cut in $\Sigma P_x^{vis\ had}$. If the dynamics of the two reactions were identical, then this would be the "true" value of $R_{NC/CC}$.

In determining $R_{NC/CC}$ one-prong events have not been used. Since one-prong events will usually correspond to low energy final hadronic states, most of these would have been rejected by the ΣP_x^{vis} cut. One-prong events are estimated to comprise only 5% of NC events with $\Sigma P_x^{vis} > 10$ GeV/c.

Defining $R'_{NC/CC}$ to be equal to the number of NC events with greater than or equal to three prongs and with $\Sigma P_x^{vis} > 10$ GeV/c divided by the number of CC events with $\Sigma P_x^{vis\ had} > 10$ GeV/c, then

$$R'_{NC/CC} = \frac{[[N - \overline{CC}' - fCC]/\varepsilon_{NC} - n - k - \overline{NC}]}{CC_{10}} ,$$

where N and $\overline{CC}'$ are the total number of events and the number of $\bar{\nu}$ CC events respectively in the subsample having $P_T < 1$ GeV/c; CC is the total number of charged current events and f is the fraction predicted to have $P_T < 1$ GeV/c; ε_{NC} is the efficiency for finding NC events in this subsample; n and k are the number of neutron and kaon induced background events; $\overline{NC}$ is the number of $\bar{\nu}$ NC events; and CC_{10} is the total number of CC events with $\Sigma P_x^{vis\ had} >$ 10 GeV/c. The EMI has been used to determine statistically the number of CC, $\overline{CC}'$, and CC_{10} events. This form assumes that neutron and kaon induced events will occur in the sample with $P_T < 1$ GeV/c with the same efficiency as NC events. The values of all these quantities are indicated in Table I. The number of CC events with $P_T < 1$ GeV/c has also been measured directly and is found to be 33.7 ± 13.1, which is in excellent agreement with the number based on the total number of CC events found (fCC). Evaluating the above expression, we find $R'_{NC/CC} = 0.40 \pm 0.14$, where the error is statistical only. The systematic errors are considered to be small compared to the statistical errors.

As a check, $R'_{NC/CC}$ has been calculated without using kinematic separation. Here the number of NC events is determined by subtracting the number of charged current event plus the sum of the various estimated backgrounds from the total number of events in the sample. A value of $R'_{NC/CC} = 0.44 \pm 0.16$ is obtained in excellent agreement with the calculation above. Although this calculation is more straightforward, it has a greater sensitivity to systematic uncertainties in the EMI estimate of the number of CC events.

For instance, a shift in the muon detection efficiency of 0.05 yields a shift in $R'_{NC/CC}$ of 0.15, while for the kinematic selection method the shift in $R'_{NC/CC}$ is only 0.03.

For comparison, $R'_{NC/CC}$ has been calculated using cuts in ΣP_x^{vis} and $\Sigma P_x^{vis\ had}$ of 5 GeV/c rather than 10 GeV/c. Here many more NC events are kept in the sample (55%), but the hadron background contamination becomes much larger. A value of $R'_{NC/CC} = 0.37 \pm 0.13$ is obtained. The agreement is extremely good.

The Monte Carlo program has been used to estimate what $R_{NC/CC}$ corresponds to the measured $R'_{NC/CC}$. Values of $R_{NC/CC}$ for different NC y distributions $[y = (E_\nu - E_\mu)/E_\nu]$ are indicated in Table II. The corrections, which include the effect of missing one-prongs, are not large compared to the statistical uncertainties and do not vary drastically for the models shown. For the Weinberg-Salam Model[10] with $\sin^2\theta_W = 0.33$, our corrected $R_{NC/CC} = 0.48 \pm 0.17$. Uncertainties in the corrections are not included in the final error on $R_{NC/CC}$.

$R_{NC/CC}$ for neutrino interactions on hydrogen has been calculated using a variety of theoretical models.[11] Among these is included the prediction based on the quark-parton, Weinberg-Salam model, which predicts $R_{NC/CC} = 0.43$ (0.36) for $\sin^2\theta_W = 0.33$ for neutrino energies below (above) charm threshold. Our measured value is in good agreement with these values but is consistent with other models also.

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7. J. Marriner, LBL Group A Physics Note #824 (unpublished).
8. R. J. Cence and V. J. Stenger, HEPG Report No. UH-511-188-75. Many calculations have been checked using another independent Monte Carlo program. The agreement between them is quite good.
9. The K_L^o induced background has also been estimated using the observed K_S^o momentum spectrum, as described in Ref. 4. All events with K_S^o in the region $4 < \Sigma P_x^{vis} < 8$ GeV/c were used for normalization. The authors state that their result is a clear overestimate since events from CC and NC neutrino interactions are included and quote their result as an upper limit. Their value, corrected to correspond to this event sample, is 10 ± 10 events.

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Figure Caption

1. Distribution of events versus P_T^2. Events with no muon candidate (all negative tracks interact within the bubble chamber) are plotted (shaded) at $P_T^2 = 0$. Also shown are the number of muons in each bin, as determined by the EMI, divided by the detection efficiency. The dashed curve is the expected distribution of muons predicted by the Monte Carlo program and normalized to the total number of muons. The sample with $P_T < 1$ GeV/c is highly enriched in NC events. The insert illustrates how P_T is defined. The selected "muon" is the negative track with the highest transverse momentum relative to the neutrino direction. P_T is the transverse momentum of the selected "muon" relative to the direction defined by the sum of the momenta of the remaining tracks ($\Sigma\vec{P}_h$).

Table I

Summary of Numbers used in Calculation of $R'_{NC/CC}$

total events	528
μ^- events (CC)	399 ± 26
μ^+ events ($\overline{CC}$)	39 ± 13
events with $P_T^2 < 1$ GeV/c (N)	134 ± 10
ν CC events with $P_T < 1$ GeV/c (fCC)	36 ± 5
$\bar{\nu}$ CC events with $P_T < 1$ GeV/c ($\overline{CC}'$)	24 ± 8
neutron induced events (n)	10 ± 7
kaon induced events (k)	6 ± 3
$\bar{\nu}$ NC events ($\overline{NC}$)	5 ± 2
ν CC events with $\Sigma P_x^{vis\ had} > 10$ GeV/c (CC_{10})	158 ± 19
predicted fraction of NC with $P_T < 1$ GeV/c (ε_{NC})	0.89 ± 0.02
predicted fraction of CC with $P_T < 1$ GeV/c (f)	0.09 ± 0.01
$R'_{NC/CC}$	0.40 ± 0.14

Table II

Corrected Values of $R_{NC/CC}$ for Various Models

Theory	NC y-distribution	$R_{NC/CC}$
V-A	Flat	0.46 ± 0.16
W-S ($\sin^2\theta_W = 0.33$)	$.75 + .25(1-y)^2$	0.48 ± 0.17
V	$.5 + .5(1-y)^2$	0.52 ± 0.18

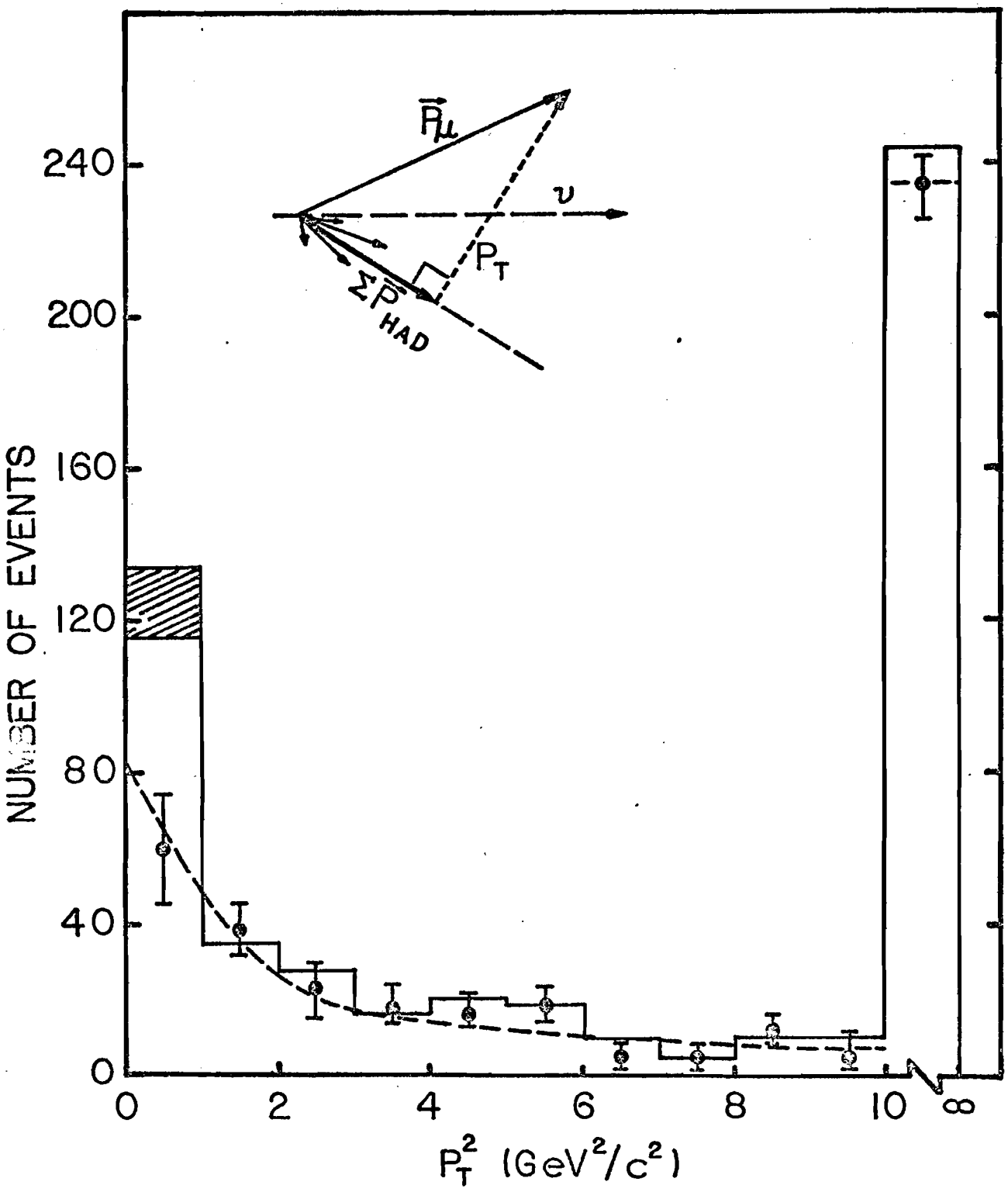
$\vec{P}_\mu$
ν
P_T
$\Sigma\vec{P}_{HAD}$
240
200
160
120
80
40
0
NUMBER OF EVENTS
0
2
4
6
8
10
∞
P_T^2 (GeV^2/c^2)

Fig. 1