Evidence for Parity Nonconservation in the Weak Neutral Current*

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Measurements of R^ν and $R^{\bar{\nu}}$, the ratios of neutral current to charged current ν and $\bar{\nu}$ cross sections, yield neutral current rates for ν and $\bar{\nu}$ that are consistent with a pure $V-A$ interaction but 3 standard deviations from pure V or pure A, indicating the presence of parity nonconservation in the weak neutral current.

The existence of a weak neutral-current interaction has been inferred from the discovery of ν and $\bar{\nu}$ inelastic collisions with nucleons that have no final-state muons.[1] This Letter reports the most recent results of our study of the nature of the weak neutral current. The 3500 events reported here are greater in number and were produced by neutrino beams of substantially higher purity than those utilized previously by us.[2] Furthermore, the data were acquired during different running conditions, making possible important tests for systematic errors. We have extracted from the data values of R^ν and $R^{\bar{\nu}}$, the ratios of neutral- to charged-current cross sections for ν and $\bar{\nu}$, which are used to obtain values of the neutral-current cross sections. The observed inequality of the ν and $\bar{\nu}$ neutral-current cross sections leads directly to the conclusion that a parity-nonconserving component is present in that current.

The apparatus, which is described in greater detail elsewhere,[3] is shown in Fig. 1(a). The spectra of the incident ν and $\bar{\nu}$ beams are shown in Fig. 1(b). Neutrino interactions which produced a hadronic cascade with energy $E_H > 4$ GeV triggered the apparatus with an efficiency greater than 99%. Counter A and the first seven calorimeters were in anticoincidence. Pulse-height information from the last eight calorimeter modules yielded the value of E_H. In addition, the wide-gap spark chambers (WGSC) were photographed in two ± 7.5° stereo views and in a 90° stereo view. Muons were identified by their presence in detectors 1 or 2 after passing through the iron hadron absorbers shown in Fig. 1(a).

Detector 1 consists of a 3.6-m× 3.6-m scintillation counter together with a 2.8-m× 2.8-m WGSC; detector 2 is solely a 2.8-m× 2.8-m WGSC. The muon identifiers have (1) high acceptance ϵ_μ for charged-current events (CC), (2) a small probability ϵ_p that hadrons associated with neutral-current (NC) interactions will punch through the absorbers to simulate muons, and (3) redundancy. In the experiments reported here, ϵ_μ is very near unity and therefore the determination of the NC/CC ratios is only weakly dependent on the details of the calculation of ϵ_μ. That calculation takes into account the spatial and energy distribution of the ν beams, muon-ionization energy loss and multiple scattering, resolution in the measurement of E_H, and the properties of the CC events as determined from these same data and reported elsewhere.[4] Values of ϵ_μ and other characteristics of the data are given in Table I. The dependence of ϵ_p on E_H and longitudinal position was obtained directly from measurements

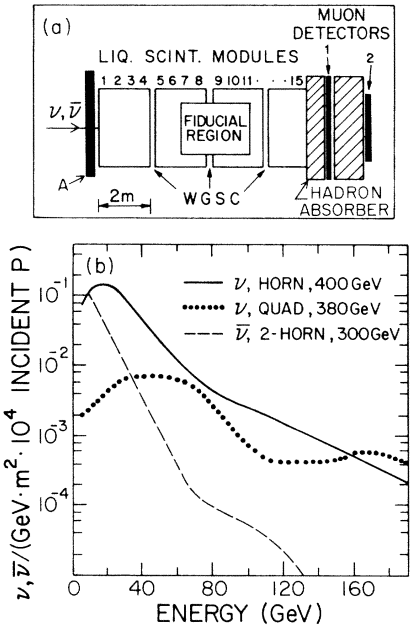

FIG. 1. (a) Sketch of the apparatus. (b) Neutrino spectra used in these experiments.

TABLE I. Relevant parameters for the four experiments reported here. The numbers of events have been corrected for muon-detection efficiency and hadron punchthrough. The parameter α, obtained from the measured CC events, indicates the composition of the beams.

Beam type	$\alpha \equiv \frac{N_{\mu^-}}{N_{\mu^-} + N_{\mu^+}}$	Number of events		Muon detection efficiency ϵ_μ		Hadron filter thickness (cm)	Hadron punch-through probability ϵ_p	
		Neutral	Charged	Det. 1	Det. 2		Det. 1	Det. 2
Single horn	0.94	266	857	0.83	a	35	0.24	~0
1974 quadrupole triplet	0.83	158	599	0.84	a	35	0.20	~0
1975 quadrupole triplet	0.86	300	1042	0.95	0.84	70	0.12	~0
Double horn with plug	0.27	69	198	0.98	0.84	70	0.07	~0

[a] Detector 2 had a different geometry for these experiments.

made on the CC data.

Candidates for both charged- and neutral-current interactions were selected from a scan of the film. The scanning efficiency was greater than 95% and was the same for NC and CC events because the scanning criteria involved only properties of event vertices. The vertex was measured in three views and its location checked for consistency with the electronic information. The small fiducial region shown in Fig. 1(a) was chosen to insure high muon-detection efficiency and good shower containment, and to reject neutron backgrounds. As with previous data,[2] no significant evidence for neutron contamination was found.

The values of R, after correction for muon efficiency and hadron punchthrough, were found to be independent of the transverse and longitudinal position of the interaction. Figure 2 illustrates this for the longitudinal coordinate. The agreement between the corrected values of R for the detectors shown in Fig. 2(b) suggests that the corrections are well understood. Comparison of the raw and corrected values of R for detector 1 shows the small magnitude of the net correction for this detector.

For each of the three measurements with nearly pure ν beams a value of R^ν for $E_H > 4$ GeV was obtained by correcting the ratio R of the NC and CC events given in Table I for the $\bar{\nu}$ content of the beams. Similarly, a value of $R^{\bar{\nu}}$ for $E_H > 4$ GeV was extracted from a measurement with a relatively pure $\bar{\nu}$ beam. These results are given with their respective values of $\langle E_{\nu,\bar{\nu}} \rangle$ in Table II. The corrections for ν_e contamination and single strange-particle production in the charged-current channel are not important relative to the statistical limitations of these data.

We previously reported the values $R^\nu = 0.11 \pm 0.05$ and $R^{\bar{\nu}} = 0.32 \pm 0.09$,[2] also for $E_H > 4$ GeV. We believe that the difference between the earlier value of R^ν and the values given in Table II underscores the difficulty of the method used to extract R^ν and $R^{\bar{\nu}}$ from the first data samples which were either statistically limited or obtained from a beam with a significant admixture of $\bar{\nu}$ ($\alpha \approx 0.62$).

To determine the space-time structure of the weak neutral current from these data, it is necessary to obtain $\sigma_N^{\bar{\nu}}/\sigma_N^\nu$ from the relation $\sigma_N^{\bar{\nu}}/\sigma_N^\nu = (R^{\bar{\nu}}/R^\nu)(\sigma_c^{\bar{\nu}}/\sigma_c^\nu)$, because the ratio of the

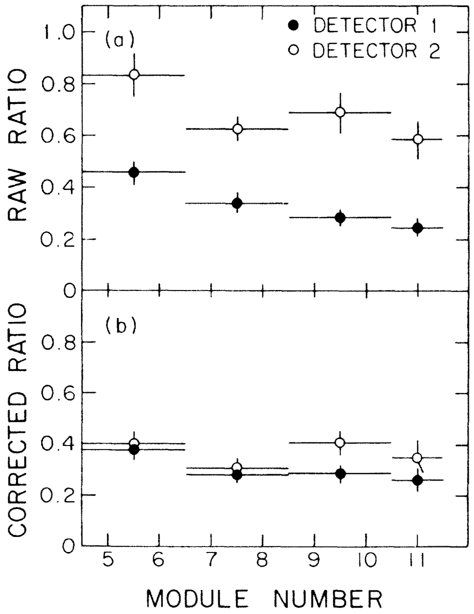

FIG. 2. (a) Raw ratio of the number of muonless events to the number with detected muons, versus module number as defined in Fig. 1(a). (b) R, the raw ratio corrected for muon detection inefficiencies and hadron punchthrough, versus module number.

TABLE II. The values of R^{ν} or $R^{\bar{\nu}}$ for $E_H > 4$ GeV.

Beam type	R^{ν}	$R^{\bar{\nu}}$	Comment
Single horn	0.31 ± 0.06		Pure ν beam, $\langle E_\nu \rangle = 53$ GeV.
1974 quadrupole triplet	0.24 ± 0.06		Mixed beam, $\langle E_\nu \rangle = 78$ GeV.
1975 quadrupole triplet	0.29 ± 0.04		Mixed beam, $\langle E_\nu \rangle = 85$ GeV.
Double horn with plug		0.39 ± 0.10	Pure $\bar{\nu}$ beam, $\langle E_{\bar{\nu}} \rangle = 41$ GeV.

charged-current cross sections $\sigma_c^{\bar{\nu}}/\sigma_c^{\nu}$ is changing with energy.[4] To obtain $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$, however, the effect of the experimental requirement $E_H > 4$ GeV must first be considered. If the neutral current has the same form as the charged current, exclusion of events with $E_H < 4$ GeV has no effect on the measured values of R^{ν} and $R^{\bar{\nu}}$. More generally, for any linear combination of V and A, $R^{\nu}(E_H > 0) \geq R^{\nu}(E_H > 4)$, while $R^{\bar{\nu}}(E_H > 0) \leq R^{\bar{\nu}}(E_H > 4)$, so that $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu} \leq [\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}]_{V-A}$. We find directly the numerical upper limit on $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$ at $\langle E_{\nu,\bar{\nu}} \rangle = 41$ from

$$\begin{aligned} \sigma_N^{\bar{\nu}}/\sigma_N^{\nu} &\leq (R^{\bar{\nu}}/R^{\nu})(\sigma_c^{\bar{\nu}}/\sigma_c^{\nu}) \\ &= [(0.39 \pm 0.10)/(0.29 \pm 0.04)](0.45 \pm 0.08) \\ &= 0.61 \pm 0.25, \end{aligned} \tag{1}$$

where R^{ν} and $R^{\bar{\nu}}$ are obtained from Table II, and $\sigma_c^{\bar{\nu}}/\sigma_c^{\nu}$ at 41 GeV is taken from Ref. 4. Note that the values of R^{ν} in Table II are approximately constant over the average energy interval from 53 to 85 GeV. This largely justifies the extrapolation of constant R^{ν} to 41 GeV, and implies, within experimental error, a linear rise with energy of the total neutral-current cross section for neutrinos.[5]

We can obtain $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$, rather than its upper limit, by correcting for unobserved events with $E_H < 4$ GeV according to various forms of the neutral-current interaction. The high energy of the neutrino beams, particularly the 1975 quadrupole triplet beam, gives rise to few events with $E_H < 4$ GeV, so that for any combination of V and A the difference between $R^{\nu}(E_H > 0)$ and the measured values of $R^{\nu}(E_H > 4)$ is negligible. The ratio $R^{\bar{\nu}}$ is more sensitive to the exact form of the interaction because of the lower $\langle E_{\bar{\nu}} \rangle$. Thus for $V-A$, $R^{\bar{\nu}}(E_H > 0) = R^{\bar{\nu}}(E_H > 4)$, while for pure V or A, $R^{\bar{\nu}}(E_H > 0) = 0.71 R^{\bar{\nu}}(E_H > 4)$; and for $V+A$, $R^{\bar{\nu}}(E_H > 0) = 0.63 R^{\bar{\nu}}(E_H > 4)$. We compare in Table III the corrected, experimental values of $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$ with the expected values of this ratio for several admixtures of V and A. It is clear that $V+A$ is ruled out. Furthermore, the experimental value for pure V or A is 3 standard deviations away from the value expected for either of those pure forms, while $V-A$ is within 1 standard deviation of the expected value.

We obtain the best fit for the form of the weak neutral current by using the general forms of the $y \equiv E_H/E_\nu$ distribution expected for any V, A combination:

$$d\sigma_N^{\nu}/dy = a + b(1-y)^2, \quad d\sigma_N^{\bar{\nu}}/dy = b + a(1-y)^2.$$

TABLE III. The measured values of $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$, after correction for the loss of events with $E_H < 4$ GeV according to the form of the weak neutral current in the first column. The corresponding values of $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$, expected from theory, are given in column three. An antiquark contribution of 5% has been assumed.

	$\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$	
Form of the weak neutral current	Corrected experimental value	Expected value
$V-A$	0.61 ± 0.25	0.38
V or A	0.40 ± 0.17	1.00
$V+A$	0.37 ± 0.16	2.65

For a $V-A$ interaction, $a \approx 1$ and $b \approx 0$, while a V or A interaction has $a = b = \frac{1}{2}$. The best fit is obtained by varying a and b until the expected value of $\sigma_N{}^{\bar{\nu}}/\sigma_N{}^{\nu}$ agrees with the corrected experimental value. For the best fit, $\sigma_N{}^{\bar{\nu}}/\sigma_N{}^{\nu} = 0.48 \pm 0.20$, $a = 0.85$, and $b = 0.15$. These results are confirmed by the measured, essentially uniform dependences of R^{ν} and $R^{\bar{\nu}}$ on E_H which do not, however, sensitively discriminate among the possible forms of the neutral current.

In summary, measurements of neutral-current and charged-current inelastic scattering of ν and $\bar{\nu}$ rule out $V+A$, and are incompatible with a pure V or pure A form for the weak neutral current. The experimental results require a significant parity-nonconserving component in the weak neutral current, and are consistent with $V-A$.

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[5] No account has been taken of a possible isoscalar component of the neutral current which is no $V-A$.

Remarks on Electromagnetic Splittings in Charmed Mesons[*]

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It has recently been predicted by De Rújula *et al.* that $m(D^+) - m(D^0) \sim 15$ MeV. The purpose of this Letter is to criticize this prediction and to examine in detail the mechanism responsible for meson mass splittings. It is concluded that electromagnetic splittings of hadrons cannot reliably be estimated using the present atomic models of hadrons. New terms are probably needed in the electromagnetic part of the potential.

The recent findings at SPEAR of a neutral particle at 1860 MeV has been interpreted as one of the predicted charmed mesons, $D^0(c\bar{p})$ or $\bar{D}^0(\bar{c}p)$. So far, the charged partners of these mesons, $D^{\pm}$ have not been detected and DGG2[1] have explained this suppression by hypothesizing that $D^{\pm} - D^0 \sim 15$ MeV. Although some suppression would exist for $D^{\pm} - D^0 \gtrsim 5$ MeV, they argue the larger splitting on the basis of ideas to be criticized in this Letter. An independent criticism of their argument has been made by Lane and Weinberg[2] and where our results overlap, I refer to their work.

The $D^{\pm} - D^0$ mass difference is believed by DGG2[1] (and by Lane and Weinberg[2]) to originate from two sources: (a) "electromagnetic" one-photon exchange binding diagrams, and (b) n-p quark mass differences due to weak and electromagnetic quark mass renormalizations. In DGG2, the total splitting was presumed to be dominated by

$$\text{mass(meson 1)} - \text{mass(meson 2)} = \sum_{i=1}^{2} (m_1{}^i - m_2{}^i) + \alpha(Q_1{}^1 Q_1{}^2 - Q_2{}^1 Q_2{}^2)\langle 1/r\rangle_{\text{meson}}, \tag{1}$$

where $m_j{}^i$ and $Q_j{}^i$ are the mass and charge of the ith quark in the jth meson. In this picture, the π splittings are not affected by $m_n - m_p$, so $\langle 1/r\rangle_{\text{meson}}$ can be estimated directly to be 1260 MeV and then $m_n - m_p$ can be found from the K splittings. From this, DDG2 arrive at $m_{D^+} - m_{D^0}$ ~ 13 MeV (the mass difference is estimated a bit higher due to the expectation that $\langle 1/r\rangle$ will increase with mass).

(i) Criticism of "electromagnetic" effects: One would expect that by using similar arguments for