Neutral-current quark coupling determination using neutrino-neutron and neutrino-proton deep-inelastic cross sections

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There is some question about the reliability of inclusive-pion-production analyses as used in previous determinations of the weak neutral-current couplings of u and d quarks. We are able to eliminate this input altogether by using new neutrino and antineutrino data for the ratio of neutral-current neutron-to-proton deep-inelastic cross sections, $\sigma(\nu n \to \nu X)/\sigma(\nu p \to \nu X)$. Another new input to our model-independent analysis is the Q^2 dependence of elastic neutrino-proton scattering. The final values determined for the neutral-current couplings are consistent with those we obtained previously. For purposes of comparison, we also present a new analysis of high-energy inclusive-pion data.

The weak neutral-current couplings of u and d quarks have recently been determined by analyses of deep-inelastic and elastic neutrino-scattering and neutrino-induced inclusive- and exclusive-pion-production processes.[1,2] However, a weak point in past determinations has been their dependence on low-energy inclusive-pion-production ($\nu N \to \nu \pi X$) data.[3] In evaluating these data, extensive parton-model assumptions are made which might be suspect, especially at such low energies.

This situation can be improved by using new results on inclusive-pion production at high energies. We present an analysis of these data[4] below. A possible problem with these data is that one must subtract out kaons and protons from the experimental numbers to obtain the desired pion multiplicities. In addition, analyses of inclusive-pion data require extensive use of final-state quark-fragmentation ideas. Fortunately, we find that all of the difficulties associated with inclusive-pion data and their analysis can be completely avoided by using new results on the ratio of neutral-current neutron-to-proton deep-inelastic cross sections $[R \equiv \sigma(\nu n \to \nu X)/\sigma(\nu p \to \nu X)]$. These give us the same isospin information about the neutral current as the inclusive-pion data and can be evaluated using only the conventional parton-model assumptions of deep-inelastic scattering. Thus, the neutral-current couplings of u and d quarks can now be determined without using any quark-fragmentation models.

The quark coupling constants to be determined are the parameters u_L, d_L, u_R, and d_R in the effective neutrino-quark interaction Lagrangian

$$\mathcal{L} = \frac{G}{\sqrt{2}} \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\,[u_L\bar{u}\gamma_\mu(1+\gamma_5)u + u_R\bar{u}\gamma_\mu(1-\gamma_5)u + d_L\bar{d}\gamma_\mu(1+\gamma_5)d + d_R\bar{d}\gamma_\mu(1-\gamma_5)d]\,. \quad (1)$$

We will restrict ourselves to values of the quark couplings which are allowed by our previous analysis[1] of deep-inelastic neutrino scattering ($\nu N \to \nu X$) off an isoscalar target. In our present analysis, the determination then begins by considering the ratio of neutron-to-proton deep-inelastic cross sections.[5] The resulting allowed values are then further restricted by an analysis[1,2] of the magnitude and Q^2 dependence of elastic neutrino-proton scattering cross sections.[6] (In our previous work[1] only the total elastic cross sections were considered.) Additional restrictions on the allowed couplings are imposed by exclusive-pion-production ($\nu N \to \nu N \pi$) data[7] evaluated as in Ref. 1. The quark coupling values resulting from the present analysis are[8,9]

$$u_L = 0.29 \pm 0.14, \quad u_R = -0.16 \pm 0.07, \quad d_L = -0.41 \pm 0.11, \quad d_R = 0 \pm 0.16, \quad (2)$$

where errors show 90% confidence limits and an overall sign convention ($u_L \geq 0$) has been assumed. These values are entirely consistent with those determined in Ref. 1 where the analysis included low-energy inclusive-pion data. The errors shown here are significantly larger than those of Ref. 1; however, no inclusive-pion data are used.

The neutral-current neutron-to-proton deep-inelastic cross section ratios, $\sigma(\nu n \to \nu X)/\sigma(\nu p \to \nu X)$, for neutrinos and for antineutrinos written in terms of the quark coupling constants u_L, d_L, u_R, and d_R assuming an SU(2)-symmetric sea are

$$R^{\nu}_{n/p} = \frac{u_L^2 + 2d_L^2 + \xi(u_R^2 + 2d_R^2) + \alpha'[u_R^2 + d_R^2 - d_L^2 + \xi(u_L^2 + d_L^2 - d_R^2)]}{d_L^2 + 2u_L^2 + \xi(d_R^2 + 2u_R^2) + \alpha'[d_R^2 + u_R^2 - u_L^2 + \xi(d_L^2 + u_L^2 - u_R^2)]}\,, \quad (3)$$

$$R^{\bar{\nu}}_{n/p}=\frac{u_R^2+2d_R^2+\bar{\xi}(u_L^2+2d_L^2)+\alpha'[u_L^2+d_L^2-d_R^2+\bar{\xi}(u_R^2+d_R^2-d_L^2)]}{d_R^2+2u_R^2+\bar{\xi}(d_L^2+2u_L^2)+\alpha'[d_L^2+u_L^2-u_R^2+\bar{\xi}(d_R^2+u_R^2-u_L^2)]}, \quad (4)$$

where

$$\xi=\frac{\int dE_\nu E_\nu \rho_\nu \int_{E_0/E_\nu}^1 dy(1-y)^2}{\int dE_\nu E_\nu \rho_\nu \int_{E_0/E_\nu}^1 dy}, \quad (5)$$

$$\bar{\xi}=\frac{\int dE_{\bar{\nu}} E_{\bar{\nu}} \rho_{\bar{\nu}} \int_{E_0/E_{\bar{\nu}}}^1 dy(1-y)^2}{\int dE_{\bar{\nu}} E_{\bar{\nu}} \rho_{\bar{\nu}} \int_{E_0/E_{\bar{\nu}}}^1 dy}, \quad (6)$$

and

$$\alpha'=\frac{3\alpha}{2+\alpha}, \quad (7)$$

with E_0 the hadronic-energy cutoff ($E_{\text{hadron}}>E_0$), ρ_ν, and $\rho_{\bar{\nu}}$ the spectra of incoming neutrinos and antineutrinos and α the ratio of antiquarks to quarks. The experimental values of these ratios with $\xi=0.21$, $\bar{\xi}=0.13$, and $\alpha'=0.12$ are[5]

$$R^{\nu}_{n/p}=1.22\pm0.35 \quad (8)$$

and

$$R^{\bar{\nu}}_{n/p}=0.53\pm0.39\,. \quad (9)$$

Using these data in conjunction with results from deep-inelastic scattering off an isoscalar target[10] gives the allowed coupling constants shown in Fig. 1. The annuli in Fig. 1 indicate values of the quark couplings allowed by the isoscalar deep-inelastic scattering data. The four regions shaded with dots show the values allowed by the above neutron-to-proton cross-section ratios at the 90% confidence level.

In order to show correlations between left and right coupling constants it is convenient to use the parametrization

$$u_L=r_L\sin\theta_L\,,\quad u_R=r_R\sin\theta_R\,,$$
$$d_L=r_L\cos\theta_L\,,\quad d_R=r_R\cos\theta_R\,. \quad (10)$$

As Fig. 1 indicates, the allowed values of r_L and r_R are quite well determined by the isoscalar deep-inelastic scattering data. However, these data give no information about the allowed values of θ_L and θ_R. Such information comes from the neutron-to-proton deep-inelastic scattering data considered above. The values of θ_L and θ_R allowed at the 90% confidence level by these ratios are shown by the regions shaded with dots in Figs. 2–4. In all three of these figures we have fixed the left radial value ($r_L=0.53$) at the center

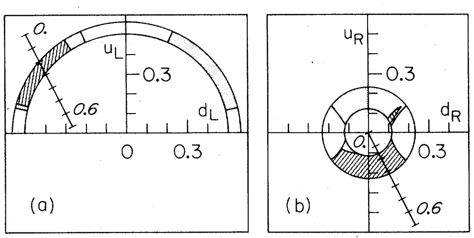

FIG. 1. The left (a) and right (b) coupling-constant planes. The lower half of (a) is omitted due to our sign convention $u_L\geq0$. The annular regions are allowed by deep-inelastic data off an isoscalar target. The regions shaded with dots are allowed by results on the ratios of neutron-to-proton deep-inelastic cross sections, and the regions shaded with lines are allowed by elastic and exclusive-pion data as well. The lines with tick marks indicate quark coupling values of the Weinberg-Salam model for $\sin^2\theta_W=0.0, 0.1, \ldots, 0.7$.

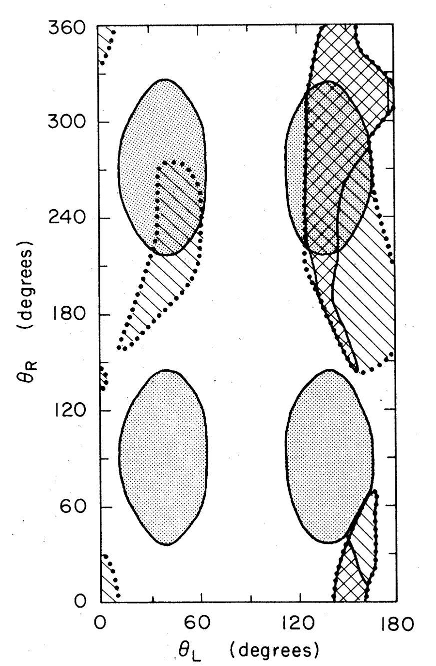

FIG. 2. The allowed angles in the coupling planes of Fig. 1 for fixed radii taken at the center of the allowed annulus ($r_L=0.53$) in the left-coupling plane and at the outer edge of the allowed annulus ($r_R=0.22$) in the right-coupling plane. The elliptical regions shaded with dots show areas allowed by the neutron-to-proton deep-inelastic cross-section ratios; going clockwise from the upper right, they are regions A, B, C, and D, respectively. The area shaded with lines and enclosed by a dotted curve is allowed by the magnitude and Q^2 dependence of elastic data. The region which is cross-hatched is allowed by both elastic and exclusive-pion-production data. The final allowed region is both cross-hatched and shaded with dots.

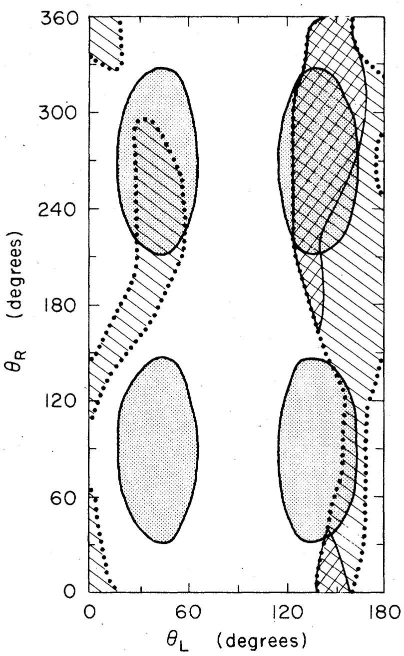

FIG. 3. Same as Fig. 2 except that the radius in the right-coupling plane (r_R=0.175) has been chosen at the center of the allowed annulus from Fig. 1(b).

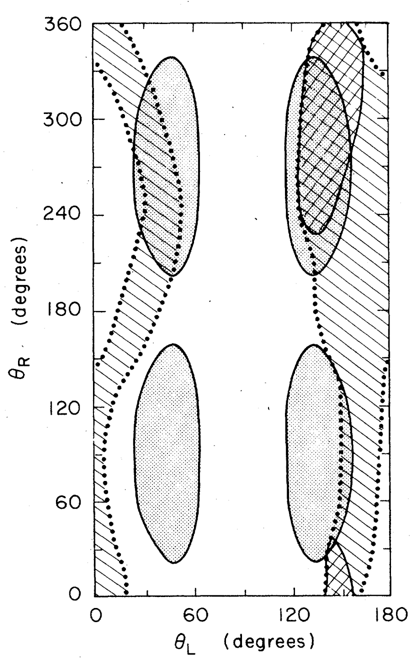

FIG. 4. Same as Fig. 2 except that the radius in the the right coupling plane (r_R=0.13) has been chosen at the inner edge of the allowed annulus from Fig. 1(b).

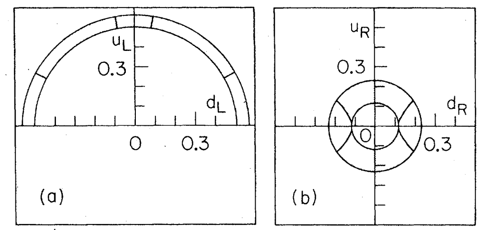

FIG. 5. The left (a) and right (b) coupling-constant planes. The annular regions are allowed by isoscalar deep-inelastic data as in Fig. 1. The regions shaded with dots are allowed by high-energy inclusive-pion-production data.

of the allowed annulus of Fig. 1(a) since variations within the allowed annulus produced little effect. In Fig. 2 we have taken the right radial value (r_R $=0.22$) at the outer edge of the allowed annulus of Fig. 1(b); in Fig. 3 we choose a radial value ($r_R=0.175$) at the center of this allowed annulus, and in Fig. 4 we take a radius ($r_R=0.13$) at the inner edge. All of the figures show four allowed regions (shaded with dots) which are in good qualitative agreement with the four regions allowed by low-energy inclusive-pion-production data (see Ref. 1). However, the allowed regions of Figs. 1–4 are considerably larger than those coming from the low-energy inclusive-pion results.

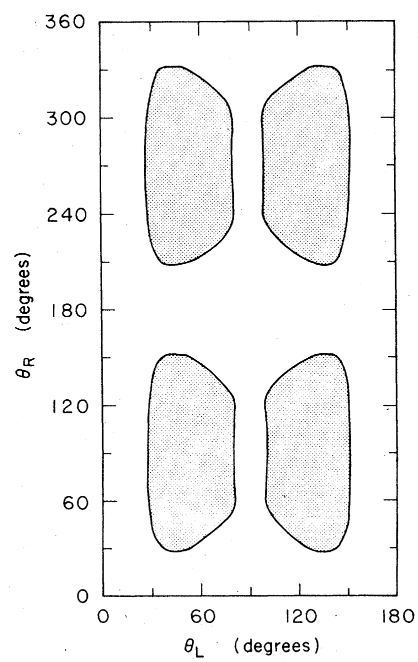

FIG. 6. The regions shaded with dots show angles in the coupling planes of Fig. 5 which are allowed by high-energy inclusive-pion data, for radii taken at the centers of the allowed annulii (r_L=0.53 and r_R=0.175).

The four regions allowed by this new analysis of neutron-to-proton deep-inelastic cross-section ratios can be further restricted by using elastic and exclusive-pion-production data as in Ref. 1. We first consider the elastic data by comparing the magnitude and Q^2 dependence of elastic neutrino-proton scattering cross sections with those for various values of the quark couplings and requiring agreement at the 90% confidence level (using a χ^2 test of fit). We have included the 20% systematic uncertainty along with the statistical errors in these data and view this as essential for a reliable analysis. The resulting allowed values of θ_L and θ_R are shown in Figs. 2–4 by the areas shaded with lines and contained by dotted curves. The consequences of the Q^2 analysis are very similar to the results of our analysis of the total elastic cross sections in Ref. 1.

We now include the restrictions imposed by exclusive-pion-production data evaluated as in Ref. 1. The values of θ_L and θ_R allowed by both the elastic and exclusive-pion analyses are the cross-hatched areas of Figs. 2–4. Note that portions of region D (the upper left-hand dotted region) are allowed by elastic data, but are completely eliminated by exclusive-pion results. Furthermore, virtually all of the overlap between the elastic and the neutron-to-proton ratio results in region B (the lower right-hand dotted region) is eliminated by the exclusive-pion data.

The final values of θ_L and θ_R which are consistent with all data are shown in Figs. 2–4 by both cross-hatching and shading with dots. The allowed values are almost exclusively in region A (the upper right-hand dotted region). Very small allowed areas also occur inside region B (the lower right-hand dotted region) for the radial values $r_R = 0.175$ and $r_R = 0.13$, but are at the edge of the 90% confidence limits. These have been ignored in the quark coupling values of Eq. (1).

The final allowed values for u_L, d_L, u_R, and d_R are plotted in Fig. 1 where they are shown shaded with lines. In Fig. 1, we have also plotted the

TABLE I. A compendium of neutral-current data compared with values predicted by the Weinberg-Salam (WS) model for $\sin^2\theta_W = 0.25$. Data are from Refs. 4–7, 10, 13, and 14. All errors shown indicate 90% confidence limits and a 30% theoretical uncertainty has been indicated for exclusive-pion-production processes.

Process	Quantity measured	Data with 90%-confidence experimental limits (statistical + systematics)	WS theory $\sin^2\theta_W = 0.25$
$\nu N \to \nu X$	R	0.295 ± 0.02	0.31
$\bar\nu N \to \bar\nu X$	R	0.34 ± 0.05	0.36
$(\nu n \to \nu X)/(\nu p \to \nu X)$	R	1.22 ± 0.56	1.13
$(\bar\nu n \to \bar\nu X)/(\bar\nu p \to \bar\nu X)$	R	0.53 ± 0.62	0.92
$\nu N \to \nu\pi X$	N_{π^+}/N_{π^-}	0.86 ± 0.32	0.86
$\bar\nu N \to \bar\nu\pi X$	N_{π^+}/N_{π^-}	1.27 ± 0.91	1.19
$\nu p \to \nu p$	R	0.11 ± 0.05	0.11
$\bar\nu p \to \bar\nu p$	R	0.19 ± 0.10	0.12
$\nu p \to \nu p\pi^0$	R	0.56 ± 0.16	0.42 ± 0.13
$\nu n \to \nu n\pi^0$	R	0.34 ± 0.15	0.43 ± 0.13
$\nu n \to \nu p\pi^-$	R	0.45 ± 0.20	0.28 ± 0.08
$\nu p \to \nu n\pi^+$	R	0.34 ± 0.12	0.28 ± 0.08
$\bar\nu N \to \bar\nu N\pi^0$	R	0.57 ± 0.16	0.39 ± 0.12
$\bar\nu n \to \bar\nu p\pi^-$	R	0.58 ± 0.26	0.29 ± 0.09
$\nu_\mu e \to \nu_\mu e$	σ/E (cm^2/GeV)	$(1.7 \pm 0.8) \times 10^{-42}$	1.4×10^{-42}
$\bar\nu_\mu e \to \bar\nu_\mu e$	σ/E (cm^2/GeV)	$(1.8 \pm 1.5) \times 10^{-42}$	1.4×10^{-42}
$\bar\nu_e e \to \bar\nu_e e$ $(1.5 < E_e < 3.0)$	σ (cm^2)	$(5.96 \pm 2.7) \times 10^{-43}$	5.94×10^{-43}
$\bar\nu_e e \to \bar\nu_e e$ $(3.0 < E_e < 4.5)$	σ (cm^2)	$(3.21 \pm 1.3) \times 10^{-43}$	2.53×10^{-43}
$e_{\rm pol} N \to eX$	$A/Q^2 \left(\frac{1}{\rm GeV^2}\right)$	$(9.5 \pm 2.6) \times 10^{-5}$	7.2×10^{-5}

quark coupling values of the Weinberg-Salam model[11] for $\sin^2\theta_W = 0.0, 0.1, \ldots, 0.7$. Clearly, our results are in excellent agreement with this model for $\sin^2\theta_W$ in the range $0.2 \leq \sin^2\theta_W \leq 0.3$.

It is interesting to go back and compare the results from our analysis of the ratios of neutron-to-proton deep-inelastic cross sections with new data[4] on high-energy inclusive-pion production ($\nu N \to \nu\pi X$) by both neutrinos and antineutrinos. We have used SLAC electroproduction results[12] to subtract out kaons, protons, and antiprotons from the total charged-particle multiplicities reported for neutrino data in order to get pion multiplicities. We have assumed that electroproduction ratios of K/π, p/π, and $\bar{p}/\pi$ in the same general kinematic range are applicable to the neutrino data. The analysis then proceeds as in Ref. 1. At the 90% confidence level, the allowed values of u_L, d_L, u_R, and d_R are shown in Fig. 5 shaded with dots and likewise the allowed values of θ_L and θ_R for the radial values $r_L = 0.53$ and $r_R = 0.175$ are shown in Fig. 6. Note that the allowed four regions are in excellent agreement with the analogous four regions coming from the neutron-to-proton cross-section ratios as shown with dots in Figs. 1 and 3. The agreement is particularly striking because it comes from two completely different types of analyses.

We conclude with a tabulation (Table I) of the experimental values[4-7,10,13,14] we have used here and in Ref. 1 to determine the neutral-current couplings[15] compared with the predictions of the Weinberg-Salam model for $\sin^2\theta_W = 0.25$.

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[1] L. F. Abbott and R. M. Barnett, Phys. Rev. Lett. 40, 1303 (1978); Phys. Rev. D 18, 3214 (1978).

[2] P. Q. Hung and J. J. Sakurai, Phys. Lett. 63B, 295 (1976); 69B, 323 (1977); 72B, 208 (1977); P. Q. Hung, ibid. 216 (1977); L. M. Sehgal, ibid. 71B, 99 (1977); E. H. Monsay, Phys. Rev. D 18, 2277 (1978); Phys. Rev. Lett. 41, 728 (1978); G. Ecker, Phys. Lett. 72B, 450 (1978); D. P. Sidhu and P. Langacker, Phys. Rev. Lett. 41, 732 (1978); Phys. Lett. 74B, 233 (1978); E. A. Paschos, Phys. Rev. D 19, 83 (1979); 15, 1966 (1977); R. E. Hendrick and L.-F. Li, *ibid.* 19, 779 (1979). Two recent papers have analyzed the Q^2 dependence of elastic νp scattering directly; M. Claudson, E. A. Paschos, and L. R. Sulak, report submitted to the XIX International Conference on High Energy Physics, Tokyo, 1978 (unpublished); H. H. Williams, report presented at the XIX International Conference on High Energy Physics, Tokyo, 1978 (unpublished).

[3] H. Kluttig *et al.*, Phys. Lett. 71B, 446 (1977).

[4] J. Marriner (neutrinos), Report No. LBL-6438, 1977, University of California Ph.D. thesis (unpublished); B. Roe (antineutrinos), in *Proceedings of the Topical Conference on Neutrino Physics at Accelerators, Oxford, 1978*, edited by D. Perkins (Rutherford Laboratory, Chilton, Didcot, Oxfordshire, England, 1978).

[5] J. Marriner (neutrinos), Report No. LBL-6438, 1977, University of California Ph.D. thesis (unpublished); W. C. Louis (antineutrinos), University of Michigan Ph.D. thesis, 1978 (unpublished).

[6] L. R. Sulak, in *Neutrinos—78*, proceedings of the International Conference on Neutrino Physics and Astrophysics, Purdue University, edited by Earle C. Fowler (Purdue Univ., Lafayette, Indiana, 1978); H. H. Williams, in *Proceedings of the Topical Conference on Neutrino Physics at Accelerators, Oxford, 1978*, edited by D. Perkins (Rutherford Laboratory, Chilton, Didiot, Oxfordshire, England, 1978); J. B. Strait and W. Kozanecki, Harvard University Ph.D. thesis, 1978 (unpublished); see also W. Lee *et al.*, Phys. Rev. Lett. 37, 186 (1976); M. Pohl *et al.*, Phys. Lett. 72B, 489 (1978); see also M. Claudson *et al.* and H. H. Williams in Ref. 2.

[7] W. Krenz *et al.*, Nucl. Phys. B135, 45 (1978); O. Erriques *et al.*, Phys. Lett. 73B, 350 (1978); see also S. J. Barish *et al.*, Phys. Rev. Lett. 33, 448 (1974); W. Lee *et al.*, *ibid.* 38, 202 (1977).

[8] If the limits on u_L, d_L, u_R, and d_R, found from our analysis of the new high-energy inclusive-pion-production data[4] are included in the final determination of quark couplings, then we obtain

$$u_L = 0.35 \pm 0.08, \quad u_R = -0.16 \pm 0.07,$$

$$d_L = -0.38 \pm 0.09, \quad d_R = 0 \pm 0.16.$$

[9] The values expected in the Weinberg-Salam model (Ref. 11) for $\sin^2\theta_W = 0.25$ are

$$u_L = 0.33, \quad u_R = -0.17,$$

$$d_L = -0.42, \quad d_R = 0.08.$$

[10] M. Holder *et al.*, Phys. Lett. 72B, 254 (1977); see also J. Blietschau *et al.*, Nucl. Phys. B118, 218 (1977); A. A. Benvenuti *et al.*, Phys. Rev. Lett. 37, 1039 (1976); P. Wanderer *et al.*, Phys. Rev. D 17, 1679 (1978); F. S. Merritt *et al.*, *ibid.* 17, 2199 (1978); P. C. Bosetti *et al.*, Phys. Lett. 76B, 505 (1978).

[11] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Physics: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksell,

Stockholm, 1968), p. 367.

[12]J. F. Martin *et al.*, Phys. Rev. D (to be published).

[13]F. J. Hasert *et al.*, Phys. Lett. 46B, 121 (1973); J. Blietschau *et al.*, Nucl. Phys. B114, 189 (1976); H. Faissner *et al.*, Phys. Rev. Lett. 41, 213 (1978); A. M. Cnops *et al.*, *ibid.* 41, 357 (1978); F. Reines *et al.*, *ibid.* 37, 315 (1976); P. Alibran *et al.*, Phys. Lett. 74B, 422 (1978); M. Haguenauer, invited talk at the XIX International Conference on High Energy Physics, Tokyo, 1978 (unpublished); the weighted averages for $\nu_\mu e$ and $\bar{\nu}_\mu e$ were taken from C. Baltay, invited talk at the XIX International Conference on High Energy Physics, Tokyo, 1978 (unpublished).

[14]C. Y. Prescott *et al.*, Phys. Lett. 77B, 347 (1978); C. Y. Prescott, invited talk at the New York American Physical Society Meeting, 1979 (unpublished).

[15]An interesting question (brought to our attention by S. Glashow, T. D. Lee, and W. Marciano) concerns the extent to which purely left-handed neutral currents can be ruled out. Taking $u_R = d_R = 0$ (but not assuming any particular $V-A$ model), the CERN-Dortmurd-Heidelberg-Saclay (CDHS) deep-inelastic total cross sections (Ref. 10) require $u_L^2 + d_L^2 = 0.306 \pm 0.025$, and we find from other types of data that best fits are obtained if $\theta_L \approx 135°$ so that $u_L \approx -d_L \approx 0.39 \pm 0.02$ (at 90% confidence). As can be seen in Fig. 1(b), CDHS data alone exclude $u_R = d_R = 0$. This exclusion is at the 4-standard-deviation level and follows primarily from the y dependence of their neutral-current data. Although high-energy inclusive-pion data (Ref. 4) and neutron-to-proton deep-inelastic data (Ref. 5) do not rule out $u_R = d_R = 0$, elastic νp data (Ref. 16) exclude $V-A$ by 2.5 standard deviations if $u_L = -d_L = 0.37$ and by more if $u_L = -d_L > 0.37$, and exclusive-pion data (Ref. 7) (at the 90% confidence level) require $u_L = -d_L > 0.37$. Turning to the question of the electron's neutral-current couplings (e_L and e_R), the $\nu_\mu e$ and $\bar{\nu}_\mu e$ data (Ref. 13) are entirely consistent with $e_R = 0$ and $-e_R = 0.37-0.39$. However, the data (Ref. 13) for $\bar{\nu}_e e$ are about 3 standard deviations from consistency with $e_R = 0$ (for all e_L allowed by $\nu_\mu e$ and $\bar{\nu}_\mu e$ data). Furthermore, the new SLAC polarized-electron asymmetry data (Ref. 14) exclude $e_R = u_R = d_R = 0$ by about 3 standard deviations for $-e_L = u_L = -d_L = 0.37-0.39$. In summary, $V-A$ is in contradition with four types of experiments.