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WEAK NEUTRAL-CURRENT INTERACTIONS**

R. Michael Barnett

Stanford Linear Accelerator Center Stanford University, Stanford, California 94305

INTRODUCTION

The structure of gauge theories of the weak and electromagnetic interactions can be studied with the weak neutral-current interactions of quarks and laptons. In gauge theories, the charged currents (CC) are related to the neutral currents (NC). In SU(2) × U(1) models, for example, the determination of the neutral currents follows from the relation (where for simplicity right-handed charged currents are ignored):

$$J_{\mu}^{NC} = \hat{q} C^{0} \gamma_{\mu} (1 + \gamma_{5}) q - 2 \sin^{2} \theta_{W} J_{\mu}^{em}$$
 (1.1)

where q is the vector (u, c, d, s, ...) and J_{μ}^{en} is the electromagnetic current. C^{o} is a matrix obtained from

$$c^{\circ} = \left[c, c^{\dagger}\right]$$
 (1.2)

where C is a matrix giving the appropriate charged current of a given $SU(2) \times U(1)$ model, i.e.,

$$J_{ij}^{CC} = \vec{q} \cdot C \gamma_{ij} (1 + \gamma_5) q.$$
 (1.3)

Thus information about neutral currents can determine the existence or non-existence of charged currents such as \bar{u}_R , $\bar{t}_{\bar{q}_R}$ or $\bar{E}^o e_R$ where n_t , n_t , and $n_{\bar{p}0}$ can be arbitrarily large.

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With the data now available, it is possible to establish uniquely the values of the neutral-rurrent couplings of c and d quarks. The roles of each type of experiment in the determination of these couplings are analyzed in Section II. The section concludes with a discussion of the implications of these results for gauge models of the weak and electromagnetic interactions. Section III contains an analysis of the neutral-current couplings of electrons. The first part of this section presents an analysis of the data based on the assumption that only one 2° boson exists. The second part discusses a model-independent analysis of parity-violation experiments. The conclusions are given in Section IV.

TI DETERMINATION OF QUARK COURLINGS

A model-independent analysis of neutrino scattering data has shown that the neutral-current couplings of u and d quarks could be uniquely datermined. The input involved four types of experiments which will be discussed separately. The work described hero was done together with Larry Abbott.

It is assumed here that there are only V and A currents. The currents of s and c quarks are neglected. The notation used in this section has \mathbf{u}_L , \mathbf{d}_L , \mathbf{u}_R and \mathbf{d}_R (L $^{\pm}$ left and R $^{\pm}$ right) as the coefficients in the effective neutral-current coupling:

$$\mathcal{L} = \frac{G}{\sqrt{2}} \tilde{v}_{\gamma_{\mu}} (1 + \gamma_{5}) v \left[v_{1} \tilde{u}_{\gamma_{\mu}} (1 + \gamma_{5}) u + u_{R} \tilde{u}_{\gamma_{\mu}} (1 - \gamma_{5}) u + d_{L} \tilde{u}_{\gamma_{\mu}} (1 + \gamma_{5}) d + d_{R} \tilde{u}_{\gamma_{\mu}} (1 - \gamma_{5}) d \right]$$
(2.1)

In the Weinberg-Salam (WS) model 2 with the Glashow-Hilppenios-Maiant (GDH) mechanism 3 incorporated, u_1 is equal to $\frac{1}{3} - \frac{2}{3} \sin^2 \theta_{\mu}$ with θ_{μ} a free parameter of the theory; u_{κ} , d_1 and d_{κ} have similar forms.

Note that there is no assumption about the bosons carrying the neutral current, only an assumption that the effective Lagrangian (2.1) holds.

A. Mautrino-Nucleon Inclusive Scattering

The calculation of deep-inelastic neutrino scattering off nucleons (wN \leftrightarrow wX) is done using the parton model. For sake of discussion only, lat us neglect sea contributions and scaling violations (from QCD). For an isosceler target, one finds that the neutral-current (NC) and charged-current (CC) cross sections for neutrinos are:

$$\sigma_{\nu}^{NC} = \frac{g_{mE}^2}{v} \int dx \ F(x) \ \left[\left(u_L^2 + a_L^2 \right) + \frac{1}{3} \left(u_R^2 + a_R^2 \right) \right] \eqno(2.2)$$

$$\sigma_{v}^{GC} = \frac{\sigma^{2} \pi \pi}{\pi} \int dx \ F(x) \ [1]$$
 (2.3)

Then the ratios for neutrinos and for antineutrinos are

$$R_{v} = \frac{d^{3}C}{d^{2}C^{2}} = \frac{\left(u_{L}^{2} + u_{L}^{2}\right) + \frac{1}{3}\left(u_{R}^{2} + d_{R}^{2}\right)}{(1)}$$
(2.4)

$$R_{\tilde{V}} = \frac{\partial^{NC}}{\sigma^{CC}} = \frac{\frac{1}{3} \left(u_L^2 + d_L^2 \right) + \left(u_R^2 + d_R^2 \right)}{\left(\frac{1}{3} \right)}$$
(2.5)

Therefore, one can determine the values of $\left(u_L^2+d_L^2\right)$ and of $\left(u_R^2+d_R^2\right)$, which are the radii in the left (L) and right (R) coupling planes. The available data are shown in Fig. 1 along with the predictions of the W5 model.

Using the data 4 of the CERN-Dortmund-Heidelberg-Saclay (CDRS) group (R_p = 0.295 ± 0.01 and R_p = 0.34 ± 0.03), the values of the radii in the L and R planes allowed at the 90% confidence level are shown in Fig. 2.

An overall sign ambiguity among the four couplings is resolved by requiring $u_i > 0$.

B. Inclusive Production of Pions by Neutrinos

The allowed radii are well determined by deep-inelastic scattaring.

It reasine to determine the allowed angles in the left and right planes.

Let us define

$$\theta_L \equiv \arctan (u_L/d_L)$$
 (2.6) $\theta_D \equiv \arctan (u_D/d_D)$

One means of determining the angles is through use of inclusive pion production (vR = vX). Again parton model assumptions are involved in the calculations. This analysis has been discussed by Sahgal, flung and Scharbach.⁵ It is assumed that pions produced in the current-fragmentation region (leading pions) are decay products of the struck quark. If a is defined as E_y/F_{had} (where $E_{had} = [total hadron energy] = energy of the struck quark), then <math>D_q^{\pi}(z)$ describes the probability that a given pion has a fraction x of energy of the struck quark q. The calculations are similar to those for inclusive deep-inelastic scattering except that the limited specification of the final scate requires that the u couplings be multiplied by $D_q^{\pi}(z)$ and d couplings by $D_q^{\pi}(z)$. Then the ratio of v^+ to v^- production for neutrinos is (neglecting sea contributions for discussion only):

$$\frac{\frac{8}{9}+}{9} = \frac{\left(u_{L}^{2} + \frac{1}{3}u_{R}^{2}\right)\overline{y}_{u}^{+} + \left(d_{L}^{2} + \frac{1}{3}d_{R}^{2}\right)\overline{y}_{d}^{+}}{\left(u_{L}^{2} + \frac{1}{3}u_{R}^{2}\right)\overline{p}_{n}^{-} + \left(d_{L}^{2} + \frac{1}{3}d_{G}^{2}\right)\overline{y}_{n}^{-}}$$
(2.76)

met e h

$$\mathbf{F}_{\mathbf{q}}^{\mathbf{T}} \stackrel{\mathbf{f}}{=} \int_{\mathbf{g}_{\mathbf{q}}}^{\mathbf{g}_{\mathbf{q}}} \mathrm{d}\mathbf{g} \, \mathbf{D}_{\mathbf{q}}^{\mathbf{T}} \tag{2.7b}$$

where one requires $x>z_1$ (leading pions), $z<z_2$ (avoids resonance region) and $E_{\rm had}>E_{\rm D}$; the values of z_1 , z_2 , and $E_{\rm D}$ depend on the particular experiment.

There are isospin relations

$$p_{a}^{T^{+}} = p_{A}^{T^{-}}$$
 and $p_{a}^{T^{-}} = p_{A}^{T^{+}}$ (2.8)

which help simplify Eq. (2.7). Furthermore, the ratio of $D_u^{\pi^+}$ to $D_u^{\pi^-}$ cam be measured in ap scattering and in charged-current neutrino scattering; the relevant ratio is

$$\eta = \int_{E_{\eta}}^{E_{2}} dz \, D_{u}^{\eta^{+}}(z) / \int_{E_{\eta}}^{T_{2}} dz \, D_{u}^{\eta^{-}}(z)$$
 (2.9)

Using Eq. (2.8) and (2.9) in Eq. 2.7, one obtains

$$\begin{pmatrix} \frac{H}{g^{+}} \\ \frac{H}{g^{-}} \end{pmatrix} = \frac{\left(u_{L}^{2} + \frac{1}{3} u_{R}^{2}\right) \eta + \left(d_{L}^{2} + \frac{1}{3} d_{R}^{2}\right)}{\left(u_{L}^{2} + \frac{1}{3} u_{R}^{2}\right) + \left(d_{L}^{2} + \frac{1}{3} d_{R}^{2}\right) \eta}$$
(2.10)

For antineutrinos, Eq. (2.10) holds if one interchanges L and R. There are corrections to Eq. (2.10) from sea contributions and from experimental afficiencies.

The data used here are low energy data from Gargamelis at the CZRM PS. These data are $\binom{N}{n} + \binom{N}{n} = 0.77 \pm 0.14$ and $\binom{N}{n} + \binom{N}{n} = 1.64 \pm 0.36$ for 0.3 < z < 0.7 and $\frac{N}{N} = 1.64 \pm 0.36$ for 0.3 < z < 0.7 and $\frac{N}{N} = 1.44$ for $\frac{N}{N} = 1.$

along with the predictions of the WS model.

Recently, high energy data have become available. The neutrino data are not for pions but for all charged particles (within the prescribed cuts); Abbott and I have used electroproduction data to estimate K and p contamination in the signal and find that the results are consistent with the Gargamelle results. The preliminary antineutrino data are also consistent with the low energy data.

We find that the high energy data do not change our conclusions or the final values of the neutral-current couplings obtained from our snalyais. However, the error bars would be increased; this is due in part to the fact that the actual quantity used (see Eq. 83 and 84 in the second paper of Ref. 1) involves differences between numbers of the same magnitude.

As can be seen in Fig. 2, the Gargamelle pion-inclusive data (even with 90% confidence levels) place severe restrictions on the allowed angles. Economy, since the ratios (Eq. 2.10) are functions of the squares of the couplings, there are various sign ambiguities.

C. Electic Hautrino-Proton Scattering

Purther determination of the allowed angles along with resolution of some sign ambiguities can be obtained from analysis^{1,7} of elastic neutrino-proton scattering ('p * 'p). Unlike the calculations of Sections IIA and B, no parton model assumptions are needed here. The matrix element for the process is

$$\left\langle p^{*}[I_{\mu}]p\right\rangle = \widetilde{u}(p^{*})\left[\gamma_{\mu}F_{1} + \frac{i\sigma_{\mu\nu}}{2\alpha}F_{2} + \gamma_{5}\gamma_{\mu}F_{A}\right]u(p) \tag{2.11}$$

The vector form factors $\left[\mathbf{F_1}(\mathbf{q}^2) \text{ and } \mathbf{F_2}(\mathbf{q}^2)\right]$ are related via CVC to

the electromagnetic form-factors of protons and neutrons:

Leovector
$$\mathbf{F}_{i} = \mathbf{F}_{i}^{p} - \mathbf{F}_{i}^{n}$$
 (2.12)

Isoscalar
$$F_i = F_i^p + F_i^n$$
 (2.13)

The isovector part of the axial-vector form-factor has been measured and has the form:

$$F_{A}(q^{2}) = \frac{1.23}{(1+q^{2}/a_{A}^{2})^{2}}$$
 (2.14)

where $u_A^2 \approx 0.79 \text{ GeV}^2$ (our results are not very sensitive to variation of u_A). The isoscalar part of the axial-vector form factor is assumed to have the same σ^2 dependence.

The appropriate factors between these four terms are obtained using the SU(6) wavefunctions of nucleons. The data of the Harvard-Pennsylvania-Wisconsin (HPM) group⁸ are $R_{_{\parallel}} \equiv \sigma^{NC}/\sigma^{CC} = 0.11 \pm 0.02$ and $R_{_{\parallel}} = 0.19 \pm 0.05$ (Statistical errors shown). These are shown in Fig. 4 slong with the predictions of the NS model.

The resolution of the sign ambiguities ressining from the pion-inclusive data is difficult to see in Fig. 2, since correlations between the left and right planes are not evident. From the pion-inclusive data shown in Fig. 2, one might think that there are 2, 3, or 4 allowed regions. The correlations can be made evident by plotting θ_1 we θ_2 (see Eq. 2.6) as in Fig. 5; this can be done "uniquely," because the radii in the left and right planes are well determined. The pion-inclusive data result in four allowed regions (appearing as chippes in Fig. 5); there would be sight regions except that $d_2 \approx 0$ so that four pairs of regions coalesce.

By "inverting" the up elastic scattering data (with the analysis described above), one can rule out two of these four regions completely and can rule out substantial portions of one other. Varying portions of two regions do remain allowed. Independent of the pion-inclusive data, the clastic data severely limit the allowed regions in coupling space.

D. Production of Exclusive Pion Modes by Meutrinos

Two of the three remaining allowed regions in Fig. 5 can be ruled out by consideration of the cross-section ratios for six exclusiva channels containing a pion:

$$\sigma(vp + vp\pi^0)/\sigma_1 \tag{2.15}$$

$$\theta(yb + yby^0)/c_1 \tag{2.16}$$

$$\sigma(va + vps^{-})/\sigma_{1}$$
 (2.17)

$$\sigma(vp + vn\pi^{+})/\sigma_{1} \tag{2.18}$$

$$\left[\sigma(\bar{\nu}p + \bar{\nu}p\pi^0) + \sigma(\bar{\nu}n + \bar{\nu}n\pi^0)\right]/\sigma_2 \qquad (2.19)$$

(2.20)

with

$$\sigma_1 \equiv \sigma(vn \rightarrow \mu^- p \pi^0)$$
 (2.21)

$$\sigma_2 \equiv \sigma(\bar{\nu}p + \mu^+ n \tau^0) \tag{2.22}$$

where recent Gargamelle data 9 were used.

 $\sigma(\tilde{v}_{D} + \tilde{v}_{D}\pi^{-})/\sigma_{\alpha}$

To analyze the data, the detailed pion-production model developed by Adier¹⁰ was used. This model is superior to all other pion-production models; it includes non-resonant production (as important feature), incorporates excitation of the A(1232) resonance, and satisfies current algebra constraints. The model gives quite good descriptions of a variety of data and is crucial for analysis of the Gargamelle data. One begins with the Born amplitudes shown in Fig. 6 which are given in terms of the form factors F_1 , F_2 and F_A (described in Section IIIC), F_{ψ} (coming from Fig. 6c) and g_{ψ} (the pion-nucleon coupling). There are two types of corrections applied.

One comes from using the current algebra relation:

$$\tau \left\{ a^{\mu} J_{\mu}^{5} \mathcal{J} \right\} = -6 \left(x_{0} \right) \left[J_{0}^{5} \mathcal{J} \right] + a^{\mu} \tau \left\{ J_{\mu}^{5} \mathcal{J} \right\}$$
 (2.23)

(where T indicates time-ordered product, and J is the week current of interest). Taking the Fourier transforms and than the matrix element between nucleon states for each piece of Eq. (2.23, one finds from PCAC that the left side is proportional to the desired matrix element $\langle Nv | J \rangle \langle O | N \rangle$. The first term on the right side leads to additional form factor terms. The second term containing the J^5 current with mxial-vector couplings, rather than the pseudo-scalar coupling assumed for the pion, implies certain vertex corrections.

The second type of correction is for final-state interactions; the outgoing pion and nucleon can resonate. In particular, for the appropriate $I=\frac{3}{2}$ terms, one must account for the \$\(^{1232}\)) resonance. There are the usual phase shifts $(a^{\frac{1}{n}})$ and enhancement effects for this F_{33} resonance. It is <u>crucial</u> to keep the non-resonant (including $I=\frac{1}{2}$) piaces; both the analysis and the data say those pieces are significant.

To avoid other (higher mass) resonances and for consistency with the aoft-pion assumptions of current algebra, it is necessary to require that the invariant mass W of the pion-nucleon system be less than 1.6 GeV. Unfortunately, the data are not svailable with this cut, and for modes with final-state neutrons it is, of course, quite difficult to obtain the invariant mass. However, the relevance of the cut to our conclusions in

mininized because: (1) most data are below the W = 1.4 GeV cut; (2) ratios of cross sections are used; (3) application of the cut to the limited experimencal mass plots available indicates a strengthening of our conclusions; and (4) the model predictions are assumed to be valid only to within 30% and the data to the 90% confidence level (this is somewhat different from the procedure followed in the first paper of Ref. 1). This fourth point is approximately equivalent to allowing any theoretical values which lie within a factor of two of the various data.

Our analysis of the six exclusive pion-production channels shows that small values of $\vartheta_L(\vartheta_L<90^\circ)$ are totally forbidden by these data. Racall that there were four regions in Fig. 5 allowed by pion-inclusive data, and that two were ruled out by the clastic data. A third region (with $\vartheta_L\approx40^\circ$ and $\vartheta_R\approx270^\circ$ in Fig. 5) is now completely ruled out. The region with $\vartheta_L\approx140^\circ$ and $\vartheta_R\approx90^\circ$, which was forbidden by elastic data, is not allowed by these data either. The exclusion of this latter region by these data alone would be such more marginal than for the regions with $\vartheta_L\approx40^\circ$. What remains is a single region (with $\vartheta_L\approx140^\circ$ and $\vartheta_R\approx270^\circ$) which is in good agreement with all four types of neutrino experiments. This unique determination can be expressed in terms of the coupling constants so that the allowed region (see Fig. 2) is

where the arrors are 90% confidence levels and an overall sign convention ($u_L \ge 0$) has been assumed.

E. Implications for Gauge Models

In examining the structure of gauge models of weak and electromagnetic interactions, one of the important questions is whether, in the context of SU(2) × U(1) models, there is any evidence for right-handed charged currents. The neutral-current results are directly relevant to this question and indicate that there are no right-handed charged currents for u or d quarks in SU(2) × U(1) models.

This conclusion can be obtained by consideration of Fig. 7 which shows the allowed regions from Fig. 2. All SU(2) x U(1) models with the left-handed coupling doublet \overline{u}_{d_1} have values in the left-coupling plans (Fig. 7s) which are indicated by the line with tick marks. These models have $\sin^2\theta_{ij}$ as a free parameter so that the position on the line (i.e., the value of $\sin^2\theta_{ij}$) is determined solely from the data. Clearly from Fig. 7a, the allowed value of $\sin^2\theta_{ij}$ is between 0.2 and 0.3.

Now looking at the right coupling plane, Fig. 7b, one sees that for the WS model the values of $\sin^2\theta_W = 0.2 - 0.3$ are also allowed there. The overall magnitude of these neutral-current couplings was dependent on the mass ratio of $m(2^O)/m(W^2)$ which is predicted by the WS model² with the minimal Riggs boson structure (one or more doublets) to be:

If this mass ratio were not as predictel, then the model would be ruled out (for example, one might find that $\sin^2\theta_W=0.1$ was required by the left-coupling plane, Fig. 7a, but $\sin^2\theta_W=0.4$ by the right-coupling plane, Fig. 7b). The auccess of those predictions of the W5 model is remarkable.

For other SU(2) × U(1) models, if one chooses $\sin^2\theta_W=0.3$ from the

left-coupling plane, then the resulting points in the right plane are determined. Shown in Fig. 7b are the points for the cases where the models have the right-handed doublets \bar{u}_{b_R} (labeled A), 11 \bar{t}_{d_R} (B) 12 , and both \bar{u}_{b_R} and \bar{t}_{d_R} (C). The latter model (C) 13 has been called the "vector" model. As can be seen, these models are ruled out by the data. Varying the ratio $m(Z^0)/m(H^{\frac{1}{2}})$ moves the points covard or away from the origin, but these models still cannot survive. There are other SU(2) × U(1) models 14 involving - $\frac{4}{3}$ and 5/3 charged quarks, and these are also ruled out.

The applicability of these results is not limited to SU(2) \times U(1) models. For example, there are two SU(3) \times U(1) models which are ruled out by these data. One 15 (labeled D in Fig. 7b) has the u quark in a right-handed singlet and the other 16 (E) has the u quark in a right-handed triplet (for this latter case the parameters of the model were chosen to place u, and d, in the allowed region in Fig. 7s).

These results also apply to the $SU(2)_L \times SU(2)_R \times U(1)$ wodel. ¹⁷ Since that wodel can be chosen to have the same values of u_L , d_L , u_R and d_R as the WS model, it is allowed by the analysis of quark couplings. In fact, Genrg1 and Weinberg18 have generalized this conclusion by showing that at zero-momentum transfer, the neutral-current interactions of neutrinos in an $SU(2) \times U(1)$ gauge theory are the same as in the corresponding $SU(2) \times U(1)$ theory if neutrinos are neutral under G.

III. DETERMINATION OF ELECTRON COUPLING

A. Analysis of Neutrino and Parity Violation Experiments

There are two types of experiments which are used to obtain information about the weak neutral-current coupling of the electron. The first is neutrino-electron scattering which can be analyzed in a model-independent fashion as was done for quarks. The second involves scarches for parity-violation in electron-nucleon interactions. This analysis requires use of the uniquely determined quark couplings obtained in Section II. However, if the results from analysis of parity-violation experiments are to be compared with those from we scattering (i.e., if g_A and g_V are to be calculated), then one must make the assumption that there is only one Z^O boson which can carry the relevant weak neutral currents.

One type of experiment involves the search for parity-violation in atomic transitions in bismuth. The details of these experiments have been given elsewhere. ¹⁹ Clearly such effects are proportional to the VA interference terms, and, in the case of bismuth, the (V _{hadron} A electron) term is completely dominant. The optical rotation ρ which is measured is than proportional to this term, i.e., $\rho = KC_{_{\mathbf{U}}}$, where K is a constant and (with the one Z^{O} assumption)

$$Q_{v} = -4 v_{had} s_{A}$$
 (3.1)

If one defines \mathbf{e}_{L} and \mathbf{e}_{R} as the coefficients in the effective neutral-current coupling:

$$\mathscr{Z} \propto \frac{G}{\sqrt{2}} \left[e_L \tilde{e} \gamma_{\mu} (1 + \gamma_5) e^{+} e_R \tilde{e} \gamma_{\mu} (1 - \gamma_5) e^{-} \right]$$
 (3.2)

thes

$$\mathbf{s}_{\mathbf{A}} \equiv (\mathbf{e}_{\mathbf{L}} - \mathbf{e}_{\mathbf{R}})$$

$$\mathbf{s}_{\mathbf{V}} \times (\mathbf{e}_{\mathbf{L}} + \mathbf{e}_{\mathbf{R}})$$
(3.3)

and

$$V_{had} = (2u_L + d_L + 2u_R + d_R)Z$$

 $+ (u_L + 2d_L + u_R + 2d_R)N$ (3.4)

where Z and N are the numbers of protons and neutrons (for bismuth, Z=83 and N = 126).

Although there is some question 20 about the atomic and nuclear calculations of K (where $e=\mathrm{KQ}_{\mathbf{q}}$), present theoretical estimates for X are such that the optical rotations o for the two transitions that have been measured are

$$P \approx 1.1 \times 10^{-9} \text{ Q radians (for 8757 $)}$$
 (3.5)

Two experiments report results consistent with zero: the Washington group²⁰ reports $c = (-0.5 \pm 1.7) \times 10^{-8}$ for the 8757 % transition while the Oxford group²¹ reports $o = (+2.7 \pm 4.7) \times 10^{-8}$ for the 6476 % transition. By contrast, the Novosibirsk experiment²² found $o = (-21 \pm 6) \times 10^{-8}$ for the 6476 % transition.

Assuming that there exists only one 2° boson, then the quark couplings (Eq. 2.24) imply that $\epsilon_{\rm A}\approx$ 0 * 0.06 for the first two experiments, and $\epsilon_{\rm A}\approx$ -0.4 $^{\pm}$ 0.17 for the Novesibirsk experiment.

The other type of experiment for which results have been reported 23 involves we elastic scattering (with $v_{\mu}e$, $\bar{v}_{\mu}e$ and $\bar{v}_{\mu}e$ measured by various groups). The cross sections for $v_{\mu}e$ and $\bar{v}_{\mu}e$ scattering are (no Z^0 assumption is involved here):

$$\frac{d\sigma^{V_{1}V_{2}}}{dE_{e}} = \frac{c m_{e}}{2\pi} \left[\left(g_{V} + g_{A} \right)^{2} + \left(g_{V} + g_{A} \right)^{2} \cdot \left(1 - \frac{E_{e}}{E_{U}} \right)^{2} + \left(g_{A}^{2} - g_{V}^{2} \right) \frac{m_{e}E_{e}}{E_{U}^{2}} \right]$$
(3.7)

where bottom signs are for antineutrinos. For $\overset{\circ}{v}_{c}$ e clastic scattering, there is an annihilation term (through a W boson), so that in Eq. (3-7) $s_{V}+s_{V}+1$ and $s_{\Lambda}+s_{\Lambda}+1$. Knowledge of these cross sections leads to

allowed regions in a $g_A - g_V$ plot which are ellipsoidal annuli.

Results have been reported for a SLAC experiment 24 involving the deep-inslastic scattering of polarized electrons off deuterium and hydrogen targets. In this experiment one measures the asymmetry between the cross sections σ_p and σ_a with electrons polarized parallel and antiparallel to the beam. If there are weak parity-violating effects, the asymmetry will be non-zero. The asymmetry is sensitive to both the V_{had} A_{elec} and A_{had} V_{elec} terms, and furthermore involves no difficult atomic or nuclear calculations.

For an isoscalar target (deuterium) the asymmetry (see Ref. 25) is, with the one Z^0 assumption:

$$\begin{split} \frac{d\sigma_{p} - d\sigma_{g}}{d\sigma_{p} + d\sigma_{p}} &= 64 \times 10^{-5} \text{ q}^{2} \left\{ \left[\frac{2}{3} (u_{L} + u_{R}) - \frac{1}{3} (d_{L} + d_{R}) \right] g_{A} \right. \\ &+ \left. \left[\frac{1 - (1 - \gamma)^{2}}{1 + (1 - \gamma)^{2}} \right] \left[\frac{2}{3} (u_{L} - u_{R}) - \frac{1}{3} (d_{L} - d_{R}) \right] g_{V} \right\} \end{split} \tag{3.8}$$

The SIAC experiment on the inelastic scattering of polarized electrons from deuterium has reported an asymmetry of $(-9.5\pm1.6)\times10^{-5}$ q^2 where q^2 is about 1.6 GeV² and y = 0.21. This is shown in Fig. 8 along with the predictions of the WS model and the "hybrid" model (described later). Similar results were obtained with hydrogen. A run at a higher value of y may be made in the future.

B. Hodel Independent Analysis of Parity Violation Experiments

Bjorkon²⁶ has shown how to analyze parity violation experiments in a model-independent fashion (in particular, there is no need to assume that there is only one 2° boson). One defines the parity-violation

parameters $\epsilon_{VA}^{\,\,e,\,q}$ and $\epsilon_{AV}^{\,\,e,\,q}$ as the coefficients in the effective Lagrangian

$$\mathcal{L} = \frac{c}{\sqrt{2}} \left[\bar{c}_{VA}^{\mu} = \left\{ c_{VA}^{\mu, \mu} \bar{u}_{V_{V}Y_{5}} + c_{VA}^{e, d} \bar{d}_{V_{L}} \gamma_{5} d \right\} \right]$$

$$+ \bar{c}_{A}^{\mu} \gamma_{5} = \left\{ c_{AA}^{e, \mu} \bar{u}_{V_{\mu}} + c_{AA}^{e, d} \bar{d}_{V_{\mu}} d \right\}$$
(3.9)

It turns out that more information can be obtained about $c_{VA}^{e,q}$ than about $c_{VA}^{e,q}$ from present data. The implications of the results of the Novosibirek, Osford and Washington experiments $^{20-22}$ in bismuth and of a "hypothetical" y=0 polarized-electron deuterium experiment are shown in Fig. 9, along with the predictions of the WS model.

C. Implications for Gauge Models

The WS model predicts $g_A = -0.5$ (independent of $sin^2 e_{ij}$) which is not consistent with the results of the Oxford and Washington experiments, but it is consistent with the results of the Novosibirsk experiment. There is an SU(2) × U(1) model which predicts $g_A \approx 0$. This model, called the "hybrid" model, is identical to the WS model except that in addition to the coupling $(\tilde{u}_0)_L$ there is a right-handed coupling $(\tilde{v}_0)_R$. However, Marciano and Sanda²⁷ have shown that higher order corrections in the hybrid model make g_A large enough to already be in marginal conflict with the Oxford and Washington experiments. Furthermore, as can be seen in Fig. 8, measurements of the polarized-electron deuteron scattering asymmetry at different values of y should clearly distinguish the hybrid and WS models (it can already be said that the hybrid model is in some conflict with the v = 0.21 measurement).

The three varieties of we scattering lead to an allowed region in the g_A^2 - g_V^2 plot as shown in Fig. 10. The WS model with $\sin^2\theta_W^2$ = 0.2-0.3

is clearly consistent with the data. Using the single 20 boson assumption, one can also plot the regions allowed by the two types of parity violation experiments.

The SLAC data rule out that version of the $SU(2)_L = SU(2)_R \times U(1)$ model which predicted no parity-violation (to Lowest order); however, other versions of that model reproduce the W5 model's predictions for all pautral-current phenomena.

IV. CONCLUSIONS

The discussion in Sections II and III indicated that most models are ruled out by present analyses, but that the MS model and cortain corresponding SU(2) × U(1) × G models curvive. In general, those models which fail are ruled out by many standard deviations. In contrast, the SU(2) × U(1) model of Weinberg and Salam agrees within 90% confidence lavels with 17 different experimental numbers as shown in the Table. Note that at the 90% confidence level one would expect about 2 of the 17 numbers to disagree with the theory; the fact that none disagrees may indicate that the error bars are conservative. Clearly one should not use only one standard deviation since then 6 numbers would be expected to disagree with theory. Left out of the Table are the results from the atomic parity-violation experiments since there are conflicting experimental results.

If one chooses to believe <u>both</u> the Oxford-Washington result and the SLAC result (and assuming there is no large y dependence), then the standard W5 model fails. However, there is a simple extension²⁸ of the model which can account for all of these phenomena. Consider the group SU(2) * U(1) * U(1)₂ where neutrinos are neutral under U(1)₂. Then all

TABLE

Comparison of WS Theory with Experiment. The theoretical numbers for exclusive pion production contain 301 errors as discussed in the text.

Process	Quantity Heasured	902 Confidence Experimental Limits (Statistical + Systematics)	WS Theory sin ² e _W = 0.25
νN → νX	R	,295 ± .02	.31
จีท → จีx	R	.34 ± .05	_36
vN → vπX	N /N -	.77 ± .22	.82
จีฅ + จีฅX	и_+/n	1.64 2 .58	1.18
∨p+vp	R	.11 ± .05	.11
ν̄p → ν̄p	ıł.	.19 ± .10	.12
νp + νpπ ^O	R	.56 ± .16	.42 ± .13
סיוחע ≁ מע	R.	.34 ± .15	.43 ± .13
va + vp*¯	R	.45 ± .20	.28 ± .08
∨ր ≁ ∨π∗ [†]	R	.34 ± .12	.28 ± .08
จีท → จัทπ°	R	.57 ± .16	.39 ± .12
vn → vpx	R	.58 ± .26	.29 ± .09
$v_{\mu}e + v_{\mu}e$	$\frac{\sigma}{E} \left(\frac{cm^2}{GeV} \right)$	(1.5 ± 1.5) × 10 ⁻⁴²	1.4 × 10 ⁻⁴²
$\bar{v}_{\mu}e \rightarrow \bar{v}_{\mu}$	σ (cm²/GeV)	(1.9±1.8) ×10 ⁻⁴²	1.4 × 10 ⁻⁴²
$\hat{v}_{e} = + \hat{v}_{e} = (1.5 < E_{e} < 3.0)$	σ (cm²)	(5.96:2.7) ×10 ⁻⁴³	5.94 × 10 ⁻⁴³
~e + ~e(3.0 < Ee < 4.5)	0 (cm²)	(3.71:3.3) ×10 ⁻⁴³	2.53 × 10 ⁻⁴³
e _{pol} D + e K	A/Q ²	(9.5 ± 2.6) × 10 ⁻⁵	7.2 = 10 ⁻⁵

charged-current interactions and all neutrino interactions are unaffected.

The parity-violation experiments here reflect the current

$$J_{11}^{NS} + \rho J_{11}^{N} = 0 (4.1)$$

where the current resulting from $\mathrm{U(1)}_{\mathrm{R}}$ is isoscalar ($\mathrm{\overline{u}u}+\mathrm{\overline{d}d}$), and p is a free parameter which is taken to be small (say 0.1 or 0.2). Since the SLAC result involves differences between u_{L} and d_{L} (u_{R} and d_{R}), it is little affected by an isoscalar piece (which is sultiplied by a small number). However, in the bismuth experiment one measures sums of u_{L} and d_{L} , and one finds that it is possible to cancel the effect due to the US current. While it is possible to achieve this cancellation, it night sees to be a rather artificial or "unnatural" solution to this problem—obtaining zero by cancelling two large numbers against each other.

For the time, it eight be beat to weit for further stonic physics results on binmuth, thallium and hydrogen before reaching final conclusions. Hometheless, the essential nature of the weak neutral-current interactions has become quite clear and the success of the Weinberg-Salam model is evident.

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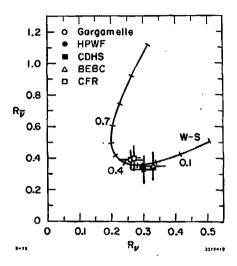


Fig. 1. The ratio of neutral to charged-current deep-inelastic sectoring cross sections for antineutrinos versus that ratio for neutrinos, The curve shows the predictions of the US model as a function of sin-(sech tick mark indicates a tenth value of sin-6y). The data are from Ref. 4.

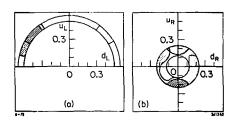


Fig. 2. The left (a) and right (b) coupling-constant rianses. The lower ball of (a) is omitted the to our sign convention up 2 0. The samular regions are allowed by deep-inclastic data. The regions shaded with dote are allowed by inclusive-pion results, and the region shaded with lites is allowed by clastic and exclusive-pion data. Unique determination of the quark coupling values is given by the region shaded with both dots and lines.

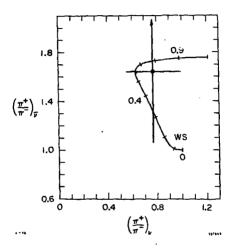


Fig. 2. The ratio of ** to ** multiplicities from inclusive-pion data for antineutrinos versus that ratio for neutrinos. The curve shows the predictions of the Weinberg-Salam model as a function of sin²by. The data are from Ref. 5, and 90% confidence limits are shown.

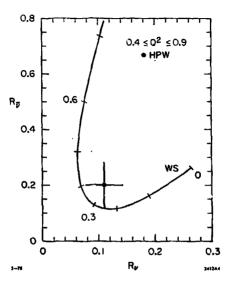


Fig. 4. The ratio of neutral to charged-current stantic up mentating cross specious for antineutries versus that ratio for neutrinos where 0.6 s $Q^4 < 0.9 \text{ GeV}^2$. The curve shows the predictions of the Meinberg-Salam model as a function of $\sin^2\theta_0$. The data are *Tron Net. 8, and only statistical uncertainties are shown (at the 90% considence level).

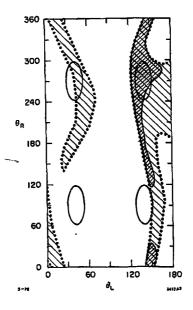


Fig. 5. The allowed angles in the coupling planes of Fig. 2 for fixed radit taken at the center of the allowed annulus (T_L = 0.53) in the infre-coupling plane and at the outer edge of the allowed annulus (T_L = 0.22) in the right-coupling plane. The ellipses indicate the regions allowed by inclusive-plon data; going closision from the upper-right, they are regions A: B, C and D, respectively. The area shaded with lines and enclosed with a dotted curve is allowed by elastic and exclusive-plon results. The area shaded with dots is the only region allowed by all data.

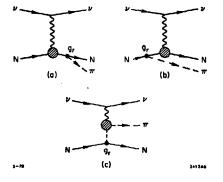


Fig. 6. Born diagrams for the exclusive-pion-production analysis. gr is the pion-nucleon coupling constant.

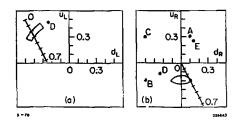


Fig. 7. Various gauge models compared with the allowed compling-constant region. The lines mark the Weinberg-Salam model for values of $\sin^2 \theta_0$ from 0.0 to 0.7. The points labeled A=2 are the predictions of various models discussed in the text. For A, B, C, and B, u_L and d_L lie within the allowed region in the left-coupling plane.

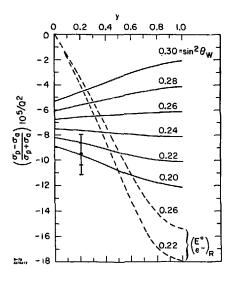
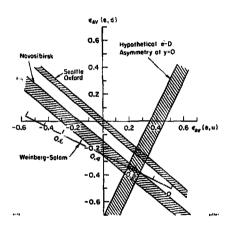


Fig. 8. The asymmetry in the SLAC experiment in which polarized electrons are inelastically scattered off deuterons, shown as a function of $y \ge (R_{\phi} - R_{\phi}^2)/R_{\phi}$. The solid (dashed) curves are the predictions of the MS ("hybrid") model for various values of $\sin^4\theta_{W}$. The data are from Raf. 24 and have $Q^2 = 1.6$ GeV² and y = 0.21. σ_{ϕ} and σ_{ϕ} refer to cross sections for electrons polarized parallel and antiparallel to the beam.



<u>Fig. 9.</u> Allowed values of $c_{0}^{q}q$, <u>assuming</u> that the measured desp-inelestic polarized-electron doubtfon scattering asymmetry represents its value at y=0.

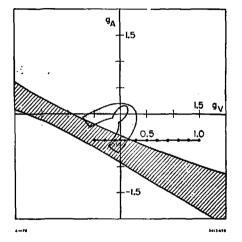


Fig. 10. Minary percent confidence limits on gA and gy of the electron. The horseshoe-shaped area at the center of the figure is the overlap region allowed by the three types of we scattering experiments. The band shaded with lines is the allowed region from the SLAC polarized-electron-deuteron scattering experiment (Ref. 24) assuming a single 20 bonon and values from Sac. II of quark couplings (including quark error bars). The upper (lower) band shaded with dots is for the Washington-Oxford (Novo-sbirsk) parity-violation experiments. The productions of the WS model sers shown for tenth values of sin²0.

WEAK NEUTRAL-CURRENT INTERACTIONS*+

R. Michael Barnett

Stanford Linear Accelerator Center Stanford University, Stanford, California 94305

T. INTRODUCTION

The structure of gauge theories of the weak and electromagnetic interactions can be studied with the weak neutral-current interactions of quarks and leptons. In gauge theories, the charged currents (CC) are related to the neutral currents (NC). In SU(2) × U(1) models, for example, the determination of the neutral currents follows from the relation (where for simplicity right-handed charged currents are ignored):

$$J_{\mu}^{RC} = \bar{q} c^{0} \gamma_{\mu} (1 + \gamma_{5}) q - 2 \sin^{2} \theta_{\mu} J_{\mu}^{en}$$
 (1.1)

where q is the vector (u, c, d, s, ...) and J_{μ}^{mn} is the electromagnetic current. C^0 is a matrix obtained from

$$c^{o} = \left[c, c^{\dagger}\right]$$
 (1.2)

where C is a matrix giving the appropriate charged current of a given SU(2) = U(1) model, i.e.,

$$J_{\mu}^{CC} = \bar{q} C \gamma_{\mu} (1 + \gamma_5) q.$$
 (1.3)

Thus information about neutral currents can determine the existence or non-existence of charged currents such as \bar{u}_R , \bar{t}_{d_R} or \bar{E}^u e_R where u_e , u_R and u_{R^0} can be arbitrarily large.

^{*}Research supported in part by the Department of Energy.

^{*}Invited talk at the Summer Institute on Particle Physics, Weak Instructions - Present and Puture, Stanford Linear Accelerator Center, Stanford, Californie, July 10-21, 1978.

With the data new available, it is possible to establish uniquely the values of the neutral-current couplings of u and d quarks. The roles of each type of experiment in the determination of these couplings are analyzed in Section II. The nection concludes with a discussion of the implications of these results for gauge models of the weak and electromagnetic interactions. Section III contains an analysis of the neutral-current couplings of electrons. The first part of this section presents an analysis of the data based on the assumption that only one 2° boson exists. The second part discusses a model-independent analysis of parity-violation experiments. The conclusions are given in Suction IV.

II. DETERMINATION OF QUARK COUPLINGS

20-11

A model-independent analysis of neutrino scattering data has shown that the neutral-current couplings of u and d quarks could be uniquely determined. The input involved four types of experiments which will be discussed separately. The work described here was done together with Larry Abbott.

It is assumed here that there are only V and A currents. The currents of s and c quarks are neglected. The notation used in this section has $\mathbf{u_L}$, $\mathbf{d_L}$, $\mathbf{u_R}$ and $\mathbf{d_R}$ (L = left and R = right) as the coefficients in the effective neutral-current coupling:

$$\mathcal{L} = \frac{G}{\sqrt{2}} \bar{v}_{Y_{\mu}} (1 + \gamma_{5}) v \left[u_{1} \bar{u}_{Y_{\mu}} (1 + \gamma_{5}) u + u_{R} \bar{u}_{Y_{\mu}} (1 - \gamma_{5}) u + d_{L} \bar{d}_{Y_{\mu}} (1 + \gamma_{5}) d + d_{R} \bar{d}_{Y_{\mu}} (1 - \gamma_{5}) d \right]$$
(2.1)

In the Weinberg-Salam (WS) model 2 with the Glushow-Hilopoulos-Mainti (GDM) sechanism 3 incorporated, u_L is equal to $\frac{1}{2} - \frac{2}{3} \sin^2 \theta_U$ with θ_U a free parameter of the theory: u_p , d_L and d_R have similar forms.

Note that there is no assumption about the bosons carrying the neutral current, only an assumption that the effective Lagrangian (2.1) holds.

A. Nautrino-Nucleon Inclusive Scattering

The calculation of deep-inelastic neutrino scattering off nucleons $(wB \to vX)$ is done using the parton model. For sake of discussion only, let us magnet sea contributions and scaling violations (from QCD). For an isoscalar target, one finds that the neutral-current (NC) and charged-current (QC) cross sections for neutrinos are:

$$\sigma_{\nu}^{NC} = \frac{G^2 \pi R}{\pi} \int dx \ F(x) \ \left[\left(u_L^2 + d_L^2 \right) + \frac{1}{3} \left(u_R^2 + d_R^2 \right) \right]$$
 (2.2)

$$\sigma_{y}^{CC} = \frac{G^{2}mP}{\pi} \int dx \ F(x) \ [1]$$
 (2.3)

Then the ratios for neutrinos and for entineutrinos are

$$R_{v} = \frac{\sigma^{BC}}{\sigma^{CC}} = \frac{\left(u_{L}^{2} + d_{L}^{2}\right) + \frac{1}{3}\left(u_{R}^{2} + d_{R}^{2}\right)}{(1)}$$
(2.4)

$$R_{\overline{U}} = \frac{\sigma^{NC}}{\sigma^{CC}} = \frac{\frac{1}{3} \left(u_L^2 + d_L^2 \right) + \left(u_R^2 + d_R^2 \right)}{\left(\frac{1}{3} \right)}$$
(2.5)

Therefore, one can determine the values of $\begin{pmatrix} u_L^2+d_L^2 \end{pmatrix}$ and of $\begin{pmatrix} u_R^2+d_R^2 \end{pmatrix}$, which are the radii in the left (L) and right (R) coupling planes. The swallable data are shown in Fig. 1 along with the predictions of the WS model.

Using the data 4 of the CERN-Dortmund-Heidelberg-Saclay (CDHS) group (R₀ = 0.295 \pm 0.01 and R₀ = 0.34 \pm 0.03), the values of the radii in the L and R places allowed at the 90% confidence level are shown in Fig. 2.

An overall sign ambiguity among the four couplings is resolved by requiring $u_{\rm c} > 0$.

B. Inclusive Production of Pions by Neutrinos

The allowed radii are well determined by deep-inelastic scattering.

It reasins to determine the allowed angles in the left and right planes.

Let us define

$$\theta_L \equiv \arctan (u_L/d_L)$$

$$\theta_B \equiv \arctan (u_B/d_B)$$
(2.6)

One means of determining the angles is through use of inclusive pion production (vN \rightarrow vX). Again parton model assumptions are involved in the calculations. This analysis has been discussed by Sehgal, Hung and Scharbach. It is assumed that pions produced in the current-fragmentation region (leading pions) are decay products of the struck quark. If z is defined as $E_q/E_{\rm had}$ (where $E_{\rm had}$ = [total hadron energy] = energy of the struck quark), then $D_q^{\rm H}(s)$ describes the probability that a given pion has a fraction z of energy of the struck quark q. The calculations are similar to those for inclusive deep-inclustic scattering except that the limited specification of the final state requires that the u couplings be multiplied by $D_{\rm u}^{\rm H}(z)$ and d couplings by $D_{\rm d}^{\rm H}(z)$. Then the ratio of v^+ to v^- production for neutrinos is (neglecting sea contributions for discussion only):

$$\frac{8'_{\frac{1}{4}}}{8!_{\frac{1}{4}}} = \frac{\left(u_{L}^{2} + \frac{1}{3}u_{R}^{2}\right)F_{u}^{\frac{1}{4}} + \left(d_{L}^{2} + \frac{1}{3}d_{R}^{2}\right)F_{d}^{\frac{1}{4}}}{\left(u_{L}^{2} + \frac{1}{3}u_{R}^{2}\right)F_{u}^{\frac{1}{4}} + \left(d_{L}^{2} + \frac{1}{3}d_{R}^{2}\right)F_{d}^{\frac{1}{4}}}.$$
(2.7a)

with

$$P_q^{\pi} \equiv \int_{\pi_1}^{\pi_2} dx \, D_q^{\pi} \tag{2.7b}$$

where one requires $z > z_1$ (leading pions), $z < z_2$ (avoids resonance resion) and $\hat{z}_{had} > \hat{z}_0$; the values of z_1, z_2 , and \hat{z}_0 depend on the particular experiment.

There are isospin relations

$$p_{ij}^{g^+} = p_{A}^{g^-}$$
 and $p_{ij}^{g^-} = p_{A}^{g^+}$ (2.8)

which help simplify Eq. (2.7). Furthermore, the ratio of $b_u^{\pi^+}$ to $b_u^{\pi^-}$ can be measured in ep scattering and in charged-current neutrino scattering; the relevant ratio is

$$\eta = \int_{z_{1}}^{z_{2}} dz \, D_{u}^{q^{+}}(z) / \int_{z_{1}}^{z_{2}} dz \, D_{u}^{q^{-}}(z)$$
 (2.9)

Using Eq. (2.8) and (2.9) in Eq. 2.7, one obtains

$$\begin{pmatrix} \frac{1}{8} + \frac{1}{8} - \frac{\left(u_L^2 + \frac{1}{3} u_R^2\right) \eta + \left(d_L^2 + \frac{1}{3} d_R^2\right)}{\left(u_L^2 + \frac{1}{3} u_R^2\right) + \left(d_L^2 + \frac{1}{3} d_R^2\right) \eta}$$
(2.10)

For antinautrinos, Eq. (2.10) holds if one interchanges L and R. There are corrections to Eq. (2.10) from mea contributions and from experimental efficiencies.

The data used here are low energy data from Garganelle⁶ at the CEEN PS. These data are $\binom{N}{\tau} + \binom{N}{\tau^{-1}} = 0.77 \pm 0.14$ and $\binom{N}{\tau} + \binom{N}{\tau^{-1}} = 1.64 \pm 0.36$ for 0.3 < z < 0.7 and $\frac{N}{\tau} = 1.64 \pm 0.36$. There are shown in Fig. 3

along with the predictions of the US model.

Recently, high energy data have become available. The neutrino data are not for pions but for all charged particles (within the prescribed cutn); Abbott and I have used electroproduction data to estimate K and p contamination in the signal and find that the results are consistent with the Gargameila results. The preliminary antineutrino data are also consistent with the low energy data.

We find that the high energy data do not change our conclusions or the final values of the neutral-current complings obtained from our analysis. However, the error bars would be increased; this is due in part to the fact that the actual quantity used (see Eq. B) and B4 in the second paper of Ref. 1) involves differences between numbers of the same magnitude.

As can be seen in Fig. 2, the Gargamelle pion-inclusive data (even with 90% confidence levels) place severe restrictions on the allowed angles. However, since the ratios (Eq. 2.10) are functions of the squares of the couplings, there are various sign embiguities.

C. Elastic Neutrino-Proton Scattering

Further determination of the allowed angles slong with res which of some sign embiguities can be obtained from analysis 1.7 of elastic neutrino-proton scattering (vp + vp). Unlike the calculations of Sections IIA and B, no parton model assumptions are needed here. The matrix element for the process is

$$\langle p'|J_{\mu}|p\rangle = \bar{u}(p')\left[\gamma_{\mu}F_{1} + \frac{i\sigma_{\mu\nu}q^{\nu}}{2\pi}F_{2} + \gamma_{5}\gamma_{\mu}F_{A}\right]u(p)$$
 (2.11)

The vector form factors $\left[F_{\frac{1}{2}}(q^2) \text{ and } F_{\frac{1}{2}}(q^2)\right]$ are related via CVC to

the electromagnetic form-factors of protons and neutrons:

Laovector
$$F_a = F_4^D - F_4^D$$
 (2.12)

Isoscalar
$$F_4 = F_4^p + F_4^n$$
 (2.13)

The isovector part of the axial-vector form-factor has been measured and has the form:

$$F_{A}(q^{2}) = \frac{1.23}{(1 + q^{2}/a_{A}^{2})^{2}}$$
 (2.14)

where $\mathbf{w}_{A}^{2}\approx0.79~\mathrm{GeV}^{2}$ (our results are not vary sensitive to variation of \mathbf{n}_{A}). The isomombar part of the axial-vector form factor in assumed to have the same \mathbf{q}^{2} dependence.

The appropriate factors between these four terms are obtained using the SU(6) wavefunctions of nucleons. The data of the Narvard-Pennsylvania-Wisconsin (HPV) group⁸ are $R_{_{\parallel}} = \sigma^{SC}/\sigma^{CC} = 0.11 \pm 0.02$ and $R_{_{\parallel}} = 0.19 \pm 0.05$ (statistical errors shown). These are shown in Fig. 4 along with the gredictions of the MS model.

The resolution of the sign ambiguities remaining from the pion-inclusive data is difficult to see in Fig. 2, since correlations between the left and right planes are not evident. From the pion-inclusive data shown in Fig. 2, one might think that there are 2, 3, or 4 allowed regions. The correlations can be made swident by plotting θ_L vs θ_R (see Eq. 2.6) as in Fig. 5; this can be donn "uniquely," because the radii in the left and right planes are well determined. The pion-inclusive data result in four allowed regions (appearing or ellipses in Fig. 5); there would be eight regions except that $d_R \approx 0$ so that four pairs of regions coalesce.

By "inverting" the up elastic scattering data (with the analysis described above), one can rule out two of these four regions completely and can rule out substantial portions of one other. Varying portions of two regions do remain allowed. Independent of the pion-inclusive data, the elastic data severely limit the allowed regions in coupling space.

D. Production of Exclusive Pion Modes by Meutrinos

Two of the three remaining allowed regions in Fig. 5 can be ruled out by consideration of the cross-section ratios for six exclusive channels containing a pion:

$$\sigma(vp \rightarrow vp\pi^0)/\sigma_1$$
 (2.15)

$$\sigma(va + var^{0})/\sigma_{1}$$
 (2.16)
 $\sigma(va + vpr^{-})/\sigma_{1}$ (2.17)

$$\sigma(vn + vp\pi^{-})/\sigma_{1}$$
 (2.17)
 $\sigma(vp + vn\pi^{+})/\sigma_{1}$ (2.18)

$$\sigma(vp + vn\pi^2)/\sigma_1$$
 (2.18)
 $\left[\sigma(\vec{v}p + \vec{v}p\pi^2) + \sigma(\vec{v}n + \vec{v}n\pi^2)\right]/\sigma_2$ (2.19)

vith

$$\sigma_1 \equiv \sigma(vn + \mu p \pi^D)$$
 (2.21)

$$\sigma_2 \equiv \sigma(\bar{v}p + \mu^{\dagger}\alpha \pi^0)$$
 (2.22)

where recent Cargamelle data 9 were used.

To analyze the data, the detailed pion-production model developed by Adier 10 was used. This model is superior to all other pion-production models; it includes non-resonant production (an important (eature), incorporates excitation of the A(1232) resonance, and satisfies current algebra countraints. The model gives quite good descriptions of a variety of data and is crucial for analysis of the Cargamelle data. One begins with the Born amplitudes shown in Fig. 6 which are given in terms of the form factors \mathbf{F}_1 , \mathbf{F}_2 and \mathbf{F}_A (described in Section IIIC), $\mathbf{F}_{\mathbf{x}}$ (coming from Fig. 6c) and $\mathbf{g}_{\mathbf{x}}$ (the pion-nucleon coupling). There are two types of corrections applied.

One comes from using the current algebra relation:

$$\tau \left\{ a^{\mu} J_{\nu}^{5} \mathcal{J} \right\} = -6 \left(\pi_{0} \right) \left[J_{0}^{5}, \mathcal{J} \right] + a^{\mu} \tau \left\{ J_{\mu}^{5} \mathcal{J} \right\}$$
 (2.23)

(where T indicates time-ordered product, and $\mathcal J$ is the weak current of interest). Taking the Fourier transforms and then the matrix element between nucleon states for each pie-x of Eq. (2.23, one finds from PCAC that the left side is proportional to the desired matrix element $\langle Bx | \mathcal J$ (0) $|B\rangle$. The first term on the right side leads to additional form factor terms. The second term containing the J^5 current with axial-vector couplings, rather than the pseudo-scalar coupling assumed for the pion, implies certain vertex corrections.

The second type of correction is for final-state interactions; the outgoing pion and nucleon can resonate. In particular, for the appropriate $I=\frac{3}{2}$ terms, one must account for the $\Delta(1232)$ resonance. There are the usual phase shifts $(a^{\frac{16}{8}})$ and enhancement effects for this P_{33} resonance. It is <u>crucial</u> to keep the non-resonant (including $I=\frac{1}{2}$) pieces; both the analysis and the data say those pieces are significant.

To avoid other (higher mass) resonances and for consistency with the soft-pion assumptions of current algebra, it is necessary to require that the invariant mass W of the pion-nucleon system be less than 1.4 GeV. Unfortunately, the data are not available with this cut, and for modes with finel-state neutrons it is, of course, quite difficult to obtain the invariant mass. Noveler, the relevance of the cut to our conclusions is

minimized because: (1) most data are below the W = 1.4 GeV cut; (2) ratios of cross sections are used; (3) application of the cut to the limited experimental mass plots available indicates a strengthening of our conclusions; and (4) the model predictions are assumed to be valid only to within 30% and the data to the 90% confidence level (this is somewhat different from the procedure followed in the first paper of Ref. 1). This fourth point is approximately equivalent to allowing any theoretical values which lie within a factor of two of the various data.

Our analysis of the six exclusive pion-production channels shows that small values of $\theta_L(\theta_L<90^\circ)$ are totally forbidden by these data. Recall that there were four regions in Fig. 5 allowed by pion-inclusive data, and that two were ruled out by the clastic data. A third region (with $\theta_L\approx40^\circ$ and $\theta_R\approx270^\circ$ in Fig. 5) is new completely ruled out. The region with $\theta_L\approx140^\circ$ and $\theta_R\approx90^\circ$, which was forbidden by elastic data, is not allowed by these data either. The exclusion of this latter region by these data alone would be much more marginal than for the regions with $\theta_L\approx40^\circ$. What remains is a single region (with $\theta_L\approx140^\circ$ and $\theta_R\approx270^\circ$) which is in good agreement with all four types of neutrino experiments. This unique determination can be expressed in terms of the coupling constants so that the allowed region (see Fig. 2) is

$$u_L = 0.35 \pm 0.07$$
 $u_R = -0.19 \pm 0.06$ (2.24)
 $d_A = -0.40 \pm 0.07$ $d_B = 0.0 \pm 0.11$

where the errors \sim 90% confidence levels and an overall sign convention ($u_L \ge 0$) has been assumed.

E. Implications for Gauge Models

In examining the structure of gauge models of weak and electromagnetic interactions, one of the important questions is whether, in the context of SU(2) × U(1) models, there is any evidence for right-handed charged curtents. The neutral-current results are directly relecant to this question and indicate that there are no right-handed charged currents for u or 4 duarks in SU(2) × U(1) models.

This conclusion can be obtained by consideration of Fig. 7 which shows the allowed regions from Fig. 2. All SU(2) \times U(1) models with the left-handed coupling doublet \overline{u}_{d} have values in the left-coupling plane (Fig. 7a) which are indicated by the line with tick marks. These models have $\sin^2\theta_{0}$ as a free parameter so that the position on the line (i.e., the value of $\sin^2\theta_{0}$) is determined solely from the data. Clearly from Fig. 7a, the allowed value of $\sin^2\theta_{0}$, is between 0.2 and 0.3.

Now looking at the right coupling plane, Fig. 7b, one sess that for the WS model the values of $\sin^2\theta_{W}=0.2-0.3$ are also allowed there. The overall magnitude of these neutral-current couplings was dependent on the mass ratio of $a(2^0)/a(W^2)$ which is predicted by the WS model² with tha minimal Riess boson structure (one or more doublets) to be:

$$\mathbf{B}_{\mathbf{Z}^{0}} = \mathbf{B}_{\mathbf{U}^{\pm}}^{-/\cos \theta_{\mathbf{U}}} \tag{2.25}$$

If this mass ratio were not as predicted, then the model would be ruled out (for example, one might find that $\sin^2\theta_W=0.1$ was required by the laft-coupling plane, Fig. 7a, but $\sin^2\theta_W=0.4$ by the right-coupling plane, Fig. 7b). The success of these predictions of the SS model is remarkable, For actor $3U(2) \times U(1)$ models, if one chooses $\sin^2\theta_W=0.3$ from the

left-coupling plane, then the resulting points in the right plane are determined. Shown in Fig. 7b are the points for the cases where the models have the right-handed doublets \bar{u}_R (labeled A). He \bar{d}_R (B) He hand both \bar{u}_R and \bar{d}_R (C). The latter model (C) Hand been called the "vector" model. As can be seen, these models are ruled out by the data. Varying the ratio $m(2^0)/m(u^4)$ moves the points toward or away from the origin, but these models still cannot survive. There are other SU(2) × U(1) models He involving - $\frac{4}{3}$ and 5/3 charged quarks, and these are also ruled out.

The applicability of these results is not limited to SU(2) x U(1) models. For example, there are two SU(3) x U(1) models which are ruled out by these data. One 15 (labeled D in Fig. 7b) has the u quark in a right-handed singlet and the other 16 (E) has the u quark in a right-handed triplet (for this latter case the parameters of the model were chosen to place u, and d, is the allowed region in Fig. 7a).

These results also apply to the $SU(2)_L \times SU(2)_R \times U(1)$ model. ¹⁷ Since that model can be chosen to have the same values of u_L , d_L , u_R and d_R as the WS model, it is allowed by the analysis of quark couplings. In fact, Georgi and Weinberg ¹⁸ have generalized this conclusion by showing that at zero-momentum transfer, the neutral-current interactions of neutrinos in an $SU(2) \times G \times U(1)$ gauge theory are the same as in the corresponding $SU(2) \times U(1)$ theory if neutrinos are neutral under G.

III. DETERMINATION OF ELECTRON COUPLING

A. Analysis of Neutrino and Parity Violation Experiments

There are two types of experiments which are used to obtain information about the weak neutral-current coupling of the electron. The first is neutrino-electron scattering which can be analyzed in a model-independent fashion as was done for quarks. The second involves searches for parity-violation in electron-nucleon interactions. This analysis requires use of the uniquely determined quark couplings obtained in Section II. However, if the results from analysis of parity-violation experiments are to be compared with those from we scattering (i.a., if g_A and g_V are to be calculated), then one must make the assumption that there is only one 2° boson which can carry the relevant weak neutral currents.

One type of experiment involves the search for parity-violation in atomic transitions in bismuth. The details of these experiments have been given elsewhere. ¹⁹ Clearly such effects are proportional to the VA interference terms, and, in the case of bismuth, the (V hadron A electron) term is completely dominant. The optical rotation ρ which is measured in then proportional to this term, i.e., $\rho = KQ_{\varphi}$, where R is a constant and (with the one 2^{O} assumption)

$$Q_a = -4 V_{had} g_A \qquad (3.1)$$

If one defines $\mathbf{e}_{\hat{\mathbf{L}}}$ and $\mathbf{e}_{\hat{\mathbf{R}}}$ as the coefficients in the affective neutral-current coupling:

$$\mathscr{Z} \propto \frac{G}{\sqrt{2}} \left[e_L \bar{e} \gamma_{\mu} (1 + \gamma_5) e + c_R \bar{e} \gamma_{\mu} (1 - \gamma_5) e \right]$$
 (3.2)

thes

$$g_A = (a_L - a_R)$$

$$g_V = (a_L + a_R)$$
(3.3)

and

$$V_{hed} = (2u_L + d_L + 2u_R + d_R)Z$$

 $+ (u_L + 2d_L + u_R + 2d_R)N$ (3.4)

where Z and N are the numbers of protons and neutrons (for bismuth, Z=83 and N = 126).

Although there is some question 20 about the atomic and nuclear calculations of K (where o * KQ $_{\rm c}$), present theoretical estimates for K are such that the optical rotations o for the two transitions that have been measured are

Two experiments report results consistent with zero: the Washington group 20 reports $\rho=(-0.5\pm1.7)\times10^{-8}$ for the 8757 % transition while the Oxford group 21 reports $\rho=(+2.7\pm4.7)\times10^{-8}$ for the 6476 % transition. By contrast, the Novomibirsk experiment 22 found $\rho=(-21\pm6)\times10^{-8}$ for the 6476 % transition.

is suming that there exists only one 2^0 boson, then the quark couplings (Eq. 2.24) imply that $g_A \approx 0^+$ 0.06 for the first two experiments, and $g_A \approx -0.4^+$ 0.17 for the Novosibirsk experiment.

The other type of experiment for which results have been reported 23 involves we clastic scattering (with $v_{\mu}e$, $\overline{v}_{\mu}e$ and $\overline{v}_{e}e$ measured by various groups). The cross sections for $v_{\mu} \gamma$ and $\overline{v}_{\mu}e$ scattering are (no Z⁰ assumption is involved here):

$$\frac{d\sigma^{V,\overline{V}}}{dE_{e}} = \frac{G}{2T} \left[\left(g_{V} + g_{A} \right)^{2} + \left(g_{V} + g_{A} \right)^{2} \left(1 - \frac{E_{e}}{E_{V}} \right)^{2} + \left(g_{A}^{2} - g_{V}^{2} \right) \frac{\pi_{2} E_{e}}{E_{V}^{2}} \right]$$
(3.2)

where bottom signs are for antineutrinos. For \bar{v}_{e} e elastic scattering, there is an annihilation term (through a W boson), so that in Eq. (3.7) $s_{V} + s_{V} + 1$ and $s_{A} + s_{A} + 1$. Knowledge of these cross sections leads to

*llowed regions in a g,-g, plot which are ellipsoidal annuli.

Results have been reported for a SLAC experiment ²⁴ involving the deep-inelastic scattering of polarized electrons off deuterium and hydrogen targets. In this experiment one measures the asymmetry between the cross sections op and on with electrons polarized parallel and antiparallel to the bean. If there are weak parity-violating effects, the asymmetry will be non-zero. The asymmetry is sensitive to both the Vhad Aelec and Ahad Velec terms, and furthermore involves no difficult atomic or nuclear calculations.

For an isoscalar target (deuterium) the asymmetry (see Ref. 25) is, with the one \mathbf{Z}^0 assumption:

$$\begin{split} \frac{d\sigma_{p} - d\sigma_{q}}{d\sigma_{p} + d\sigma_{p}} &= 64 \times 10^{-5} \text{ q}^{2} \left\{ \left[\frac{2}{3} (u_{L} + u_{R}) - \frac{1}{3} (d_{L} + d_{R}) \right] g_{A} + \left[\frac{1 - (1 - y)^{2}}{1 + (1 - y)^{2}} \right] \left[\frac{2}{3} (u_{L} - u_{R}) - \frac{1}{3} (d_{L} - d_{R}) \right] g_{V} \right\} \end{split}$$
(3.8)

The SLAC envertment on the inelestic scattering of polarized electrons from deuterium has reported an asymmetry of $(-9.5\pm1.6)\times10^{-5}~\text{q}^2$ where q^2 is about 1.6 CeV^2 and y=0.21. This is shown in Fig. 8 along with the predictions of the W5 model and the "hybrid" model (described later). Similar results were obtained with hydrogen. A run at a higher value of y may be made in the future.

B. Model Independent Analysis of Parity " plation Experiments

Sjorken²⁶ has shown how to analyze p. 'ty violation experiments in a model-independent fashion (in particular, there is no need to assume that there is only one 2° boson). One defines the parity-violation

parameters $\epsilon_{VA}^{\epsilon,\,q}$ and $\epsilon_{AV}^{\epsilon,\,q}$ as the coefficients in the effective Lagrangian

$$\mathcal{L} = \frac{G}{\sqrt{2}} \left[\bar{c}_{VA}^{\mu} = \left\{ c_{VA}^{e,u} \bar{u}_{V_{V}} v_{S} + c_{VA}^{e,d} \bar{d}_{V_{U}} v_{S} \right\} \right]$$

$$+ \bar{c}_{V}^{\mu} v_{S} = \left\{ c_{AV}^{e,u} \bar{u}_{V_{U}} + c_{AV}^{e,d} \bar{d}_{V_{U}} d \right\}$$
(3.9)

It turns out that zore information can be obtained about $c_{\Lambda V}^{e,q}$ than about $c_{V\Lambda}^{e,q}$ from present data. The implications of the results of the Novosibirek, Oxford and Washington experiments $^{20-22}$ in bismuth and of a "hypothetical" y=0 polarized-electron deuterium experiment are shown in Fig. 9, along with the predictions of the Wi model.

C. Implications for Gauge Models

The WS model predicts $\mathbf{g}_{A} = -0.5$ (independent of $\sin^2\theta_{41}$) which is not consistent with the results of the Oxford and Washington experiments, but it is consistent with the results of the Novosibirsk experiment. There is an SU(2) × U(1) model which predicts $\mathbf{g}_{A} \approx 0$. This model, called the "hybrid" model, is identical to the WS model except that in addition to the coupling $(\nabla e)_{L}$ there is a right-handed coupling $(\nabla e)_{R}$. However, Marciano and Sanda²⁷ have shown that higher order corrections in the hybrid model make \mathbf{g}_{A} large amough to already be in marginal conflict with the Oxford and Washington experiments. Furthermore, as can be seen in Fig. 8, measurements of the polarized-electron deuteron scattering asymmetry at different values of \mathbf{y} should clearly distinguish the hybrid and WS models (it can already be said that the Nobel a model is in some conflict with the $\mathbf{y} = 0.21$ measurement).

The three varieties of we scattering lead to an allowed region in the $s_A=\tau_V$ plot as shown in Fig. 10. The WS model with $\sin^2\theta_W=0.2-0.3$

is clearly consir out with the data. Using the single 2° boson essumption, one can also plot the regions allowed by the two types of parity violation experiments.

The SLAC data rule out that version of the $SU(2)_{\xi_i} \times SU(2)_{\xi_i} \times U(1)$ model which predicted no parity-violation (to lowest order): however, other versions of that model reproduce the W5 model's predictions for all neutral-current phenomena.

IV. CONCLUSIONS

The discussion in Sections II and III indicated that most models are ruled out by present analyses, but that the MS model and certain corresponding SU(2) × U(1) × G models survive. In general, those models which but are ruled out by many standard deviations. In contrast, the SU(2) × U(1) model of Mcimberg and Selem agrees within 901 confidence lawels with 17 different experimental numbers as shown in the Table. Note that at the 902 confidence lawel one would expect about 2 of the 17 numbers to disagree with the theory; the fact that none disagrees may indicate that the error bars are conservative. Clearly one should not use only one standard deviation since then 6 numbers would be expected to disagree with theory. Left out of the Table are the results from the atomic parity-violation experiments since there are conflicting experiments results.

If one chooses to selleve both the Oxford-Washington result and the SLAC result (and assuming there is no large y dependence), then the stendard WS model fails. However, there is a simple extension 28 of the model which can account for all of these phenomenas. Consider the group $SU(2) \times U(1) \times U(1)_R$ where neutrinos are neutral under $U(1)_R$. Then all

TABLE

Comparison of WS "eary with Experiment. The theoretical numbers for exclusive pion production contain 30" errors as discussed in the taxt.

Process	Quantity Measured	902 Confidence Experimental Limits (Statistical + System: tics)	us Theory sin ² 0, = 0.25
VK + VX	R	.295 ± .02	.31
ūn → ūx	R	.34 1 .05	.36
Xev + No	N,+/N,-	.77 + .22	.82
υμ → υπ χ	N_+/N	1.64 : .58	1.18
υρ • ∨ρ	"R"	,11 ± .05	.11
⊽p + ⊽p	R	.19 + .10	.12
νp + νpτ ^σ	R	.56 ± .16	.42 ± .13
Va + va×°	R.	.34 ± .15	.43 ± .13
va ≁ vp≋	R	.45 ± .20	.28 ± .08
vp ∻ vnx [†]	R	.34 ± .12	.28 ± .08
จีท → จีหะ°	R	.57 • .16	.39 ± .12
Va → Vpx T	R	.58 : .26	.29 ± .09
v _p e + v _p e	g (cm²) E (cev)	(1.5 : 1.5) × 10 ⁻⁴²	1.4 = 10-42
จั _ย น + จั _ย ต	σ (cm²) ε (GeV)	(1.9:1.8) - 10-42	1.4 = 10 ⁻⁴²
$\tilde{v}_{a}e+\tilde{v}_{e}a(1.5<\xi_{c}<3.0)$	o (cm²)	(5.96:2.7) - 10 ⁻⁴³	5.94 × 16 ⁻⁴³
v_e+v_e(3.0 < € < 4.5)	o (cm²)	(3,21±1,3) ×10 ⁻⁴³	2.53 = 10 ⁻⁴³
epol D + e x	A/Q ²	(9,5 +2 e) +10 ⁻⁵	7.2 4 10 ⁻⁵

charged-current interactions and all neutrino interactions are unaffected. The parity-violation experiments here reflect the current

$$J_u^{NS} + \rho J_u^{I} = 0$$
 (4.1)

where the current resulting from U(1)_R is isoscalar (ūu + d̄d), and p is a free parameter which is taken to be small (say 0.1 or 0.2). Since the SLAC result involves differences between u_L and d_L (u_R and d_R), it is little affected by an isoscalar piece (which is multiplied by a small number). However, in the bismuth experiment one measures sums of u_L and d_R, and one finds that it is possible to cancel the effect due to the W5 current. While it is possible to achieve this cancellation, it might seem to be a rather actificial or "unnatural" solution to this problem—obtaining zero by exception two large numbers against each other.

For the time, it might be best to vait for further atomic physics results on bismuth, thallium and hydrogen before reaching final conclusions. Mometheless, the assential nature of the weak neutral-current interactions has become quite clear and the success of the Weinberg-Salam model is evident.

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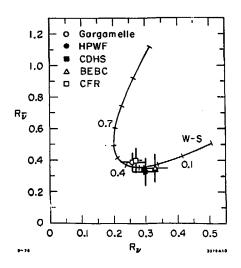
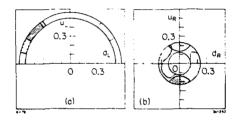


Fig. 1. The ratio of neutral to charged-current deep-inelastic scattering cross sections for antineutrinos versus that ratio for neutrinos, The curve shows the predictions of the US model as a function of sin by (each tick mark indicates a tenth value of sin by). The data are from Ref. 4.



Yig. 2. The left (a) and right (b) coupling-constant planes. The lower half of (a) is outsted due to our sign convention u_1 ? 0. The annular regions are allowed by deep-inclastic data. The regions shaded with dots are allowed by inclusive-pion results, and the region shaded with lines is allowed by elastic and settlestive-pion data. Unique determination of the quark coupling values is given by the region shaded with both dots and lines.

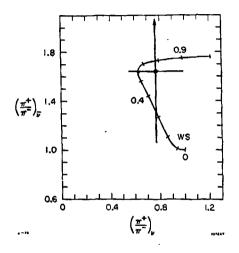


Fig. 3. The ratio of ** to n° multiplicities from inclusive-pion data for antineutrinos versus that ratio for neutrinos. The curve shows the predictions of the Weisherg-Salam model as a function of sin²cy. The data are from Ref. 5, and 90% confidence limits are shown.

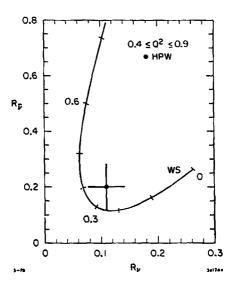
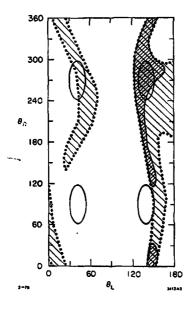
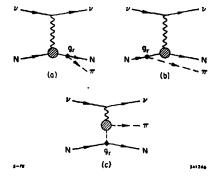


Fig. 4. The ratio of neutral to charged-current elastic vp scattering cross sections for antineutrinos versus that ratio for neutrinos where $0.4 \times Q^4 \times Q.9 \text{ GeV}^2$. The curve shows the predictions of the Neinberg-Salam model as a function of $\sin^2 q_c$. The data are from Ref. 8, and only statistical uncertainties are shown (at the 90% confidence level).



Pig. 1. The allowed angles in the coupling planes of Fig. 2 for fixed radii taken at the center of the allowed annulus (r₁ = 0.51) in the left-coupling planes and at the outer edge of the allowed annulus (r₂ = 0.22) in the right-coupling plane. The ellipses indicate the regions allowed by inclusive-plon data; going clockwise from the upper-right, they are regions allowed by inclusive-plon data; going clockwise from the upper-right, they are regions Alpo, C and D, respectively. The area shaded with lines and enclosed with a dotted curve is allowed by elastic and exclusive-plon results. The area shaded with dots in the only region allowed by all data.



<u>Pig. 6.</u> Born diagrams for the exclusive-pion-production analysis. g_{χ} is the pion-nucleon coupling constant.

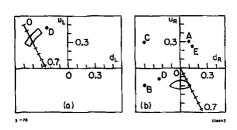


Fig. 7. Various gauge models compared with the allowed coupling-constant region. The lines mark the Weinberg-Sales model for values of sin-by from 0.0 to 0.7. The points labeled A-E are the predictions of various models discussed in the text. For A, B, C, and E, ut and dt lie within the allowed region in the left-coupling plane.

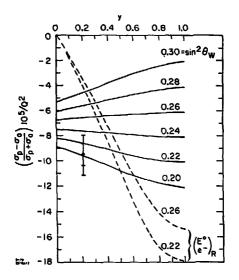


Fig. 8. The asymmetry in the SLAC experiment in which polarized electrons are inelastically scattered off deuterons, shown as a function of $y \ni (\mathbb{E}_q = \mathbb{E}_p)/\mathbb{E}_q$. The solid (dashed) curves are the predictions of the \mathbb{N} ("hybrid") model for various values of $\sin^2 \theta_0$. The data are from Ref. 24 and have $\mathbb{Q}^2 = 1.6 \text{ GeV}^2$ and y = 0.21. σ_p and σ_q refer to cross sections for electrons polarized parallel and antiparallel to the best-

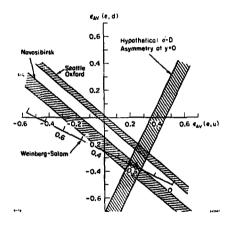


Fig. 9. Allowed values of $c_{0}^{2}q^{2}$, assuming that the measured deep-inclantic polarized-electron deuteron scattering asymmetry represents its value at y=0.

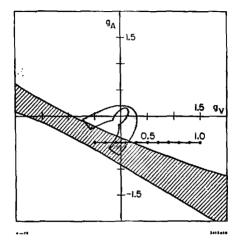


Fig. 10. Minety percent confidence limits on gA and gy of the electron. The horseshoped area at the center of the figure is the overlap region allowed by the three types of we scattering experiments. The band shaded with lines is the allowed region from the SLAC polarized-electron-deuteron scattering experiment (Ref. 73) assuming a single 20 boson and values from Sac. It of quark couplings (including quark error bars). The upper (lower) band shaded with dots is for the Machington-Ontord (Novo-sibirsk) parity-violatio: experiments. The predictions of the MU model are shown for tenth values of sia²Cu.