RESTRICTIONS ON MODELS OF THE WEAK INTERACTIONS

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ABSTRACT

The constraints which present data and a few, plausible theoretical assumptions impose upon quark-lepton models of the weak interactions are analyzed. While study of a given type of experiment usually allows many models, among all possible $SU(2) \times U(1)$ models few survive if all data and these theoretical restrictions are used. It is shown that even these few could be eliminated by data expected in the near future.

(Submitted to the Physical Review.)

^{*} Supported by the Energy Research and Development Administration.

I. Introduction

With an increasing amount of data becoming available on the weak interactions, the space in which theory can operate has been sharply restricted. If all present data are taken as completely accurate and if certain theoretical and aesthetical constraints are assumed, then one can rule out almost all possible $SU(2) \times U(1)$ models.

A set of restrictions will be described here for the construction of models of the weak interactions of quarks and leptons. In this context only models in the general framework of the Weinberg-Salam $SU(2) \times U(1)$ gauge theory¹ of weak and electromagnetic interactions are considered. All such models with singlets, doublets, triplets and/or other representations of $SU(2)_{weak}$ are included.

In order to reach any conclusions, it is necessary to assume that published data (or a particular set of the data) are correct and that the present theoretical interpretation of those results is correct. If the data changes or if one wants to employ different theoretical constraints, the analysis given here still applies but would be slightly amended.

There are, currently in progress, experiments searching for weak parityviolating, neutral-current effects in atomic $physics^{2,3}$ which will soon provide a further and severe limitation on the models considered. But this constraint is not used here since no results have been published yet.

There are four models which approximately satisfy the particular set of constraints given below. Some of these models are not very compelling, and any of them could be ruled out by improved data or the atomic physics experiments. One of the constraints will later be weakened, allowing several more models. In Section II the set of restrictions to be used here is given. All of the necessary formulas to calculate model predictions are shown in Section III. The allowed models are found in Section IV and they are discussed in the context of the experimental data.

II. Constraints on Models

A starting restriction for these models is the very qualitative requirement of simplicity and symmetry. There is, of course, also a certain amount of prejudice in some of the constraints given below and if there is a rationale, one might modify one or two of them. The constraints used here are:

(1) In order to have a renormalizable gauge theory, one must have a cancellation of VVA triangle anomalies⁴. This can be done within the quark sector and within the lepton sector separately by having an analogous right-handed current (V + A) for each left-handed current (V-A); such models are usually called "vector-like." Alternatively if the appropriate quark and lepton charges sum to zero (using left-handed particles and right-handed antiparticles), the anomalies can be cancelled.

(2) It will be required not only that there is a Glashow-Iliopoulos-Maiani (GIM) mechanism⁵ for the cancellation of strangeness-changing neutral-currents, but that it occurs "naturally." "Naturalness" is defined in Ref. 6; it is the condition that the GIM mechanism "follows from the group and representation content of the theory, and does not depend on the values taken by the parameters of the theory" (such as Cabibbo-type angles). Models with natural GIM are here defined as those in which all charge $-\frac{1}{3}$ quarks have the same values of τ_{3L} , of τ_{3R} , or $\overline{\tau}_{L}^{2}$ and of $\overline{\tau}_{R}^{2}$ (separately), where τ is the weak isospin (from SU(2)_{weak}) for left- or for right-handed currents. This requirement will

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not be enforced for quarks of any other charge, although one could do that (if no charm-changing neutral-currents are found, it will probably be necessary for $\frac{2}{3}$ charged quarks). This constraint for charge - $\frac{1}{3}$ quarks will be weakened later (Section IV).

(3) The left-handed quark and lepton couplings are experimentally equal (modulo the Cabibbo angle). It will be assumed that this quark-lepton uni-versality is "natural" in the sense that if the u and d quarks are in weak doublets, then the $\nu_{\rm e}$ and e are in doublets (and similarly for other multiplets); the equality of couplings should not be obtained through any mixing of particles. It is further assumed that the left-handed electron and muon are also in the same weak SU(2) representation (that their equality of couplings is "natural").

In addition to these essentially theoretical constraints, models must be consistent with all data:

(4) In charged-current, deep-inelastic neutrino scattering $(\nu N \rightarrow \mu + X)$, the ratio R_c of antineutrino to neutrino cross sections appears to become about double that expected at the highest energies. In addition the antineutrino ydependence changes as a function of energy, see Figs. 1 and 2. The Harvard-Pennsylvania-Wisconsin-Fermilab $(HPWF)^{7,8}$ and Cal Tech-Fermilab $(CF)^9$ data both show these effects. An antineutrino bubble-chamber experiment¹⁰ does not see the change in the y-dependence, but at the present level of their statistics, it is not clear that they conflict with the results of HPWF and CF. It is difficult to understand these two phenomena $(R_c and < y >)$ without righthanded currents; even the increasing sea contributions due to asymptotic freedom corrections appear to be inadequate.¹¹ It will be assumed for most models that there must be a right-handed coupling of the u quark to a heavy, $-\frac{1}{3}$

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charged quark (mass 4-6 GeV) or a coupling of the d quark to a heavy, $-\frac{4}{3}$ charged quark.

(5) There are three experiments with results for neutral-current, deepinelastic neutrino scattering ($\nu N \rightarrow \nu + X$). As can be seen in Fig. 3, the data of HPWF¹², CF¹³ and Gargamelle¹⁴ are in reasonably good agreement (note the theoretical correction of HPWF and CF data described in the figure caption). Purely vector neutral currents appear to be excluded. There are also neutralcurrent, elastic νp scattering results which appear to exclude the vector model: $R_N \equiv \sigma (\nu p \rightarrow \nu p)/\sigma (\nu n \rightarrow \mu p) = 0.17 \pm 0.05$ (Harvard-Pennsylvania-Wisconsin¹⁵) and 0.23 ± 0.09 (Columbia-Illinois-Rockefeller¹⁶) and $R_{\overline{\nu}} =$ 0.2 ± 0.1 (HPW¹⁷) which gives $R_N \equiv \sigma (\overline{\nu} p \rightarrow \overline{\nu} p)/\sigma (\nu p \rightarrow \nu p) = 0.4 \pm 0.2$ (HPW). Interpretation of these elastic νp results for various models is given in Refs. 18-19, but with present statistics it is difficult to distinguish among models other than the vector model.

(6) There are several experiments 20,21,22 which give cross sections or upper limits for $\nu_{\mu} e$, $\overline{\nu}_{\mu} e$ and $\overline{\nu}_{e} e$ elastic scattering. These set bounds on the possible values of the vector and axial-vector parts (g_V and g_A , defined in Section III) as shown in Fig. 4 (note that there are model-dependent corrections for $\overline{\nu}_{\mu} e$ which usually increase the "radii" of those curves).

(7) While there are not any published results from the search for parityviolating neutral-current effects in atomic physics, the predictions of models will be given and soon, this will be another constraint. These predictions are shown for the models of Section IV in Table I.

(8) There are an assortment of other phenomenological restrictions which will not be discussed here. Among them are the $\Delta I = \frac{1}{2}$ rule, the existence of

a heavy lepton, the magnitude of $R(e^+e^-) = \sigma (e^+e^- \rightarrow hadrons)/\sigma (e^+e^- \rightarrow \mu^+\mu^-)$ and the violation of CP.

III. Calculation of Charged- and Neutral-Current Scattering

One defines the usual scaling variables $x = -q^2/2m(E-E')$ and y = (E-E')/Ewhere E(E') is the incoming (outgoing) lepton lab energy, m is the proton mass and q is the four-momentum of the exchanged W^{\pm} or Z^{O} boson. While the ratio of the Z^{O} to W^{\pm} mass is uniquely defined in the Weinberg-Salam-GIM model, it can be different in other models; so define κ :

$$\kappa = \frac{M(Z^{O})_{model}}{M(Z^{O})_{W-S-GIM}}$$
(3.1)

(where κ is absent when these formulas are applied to charged currents).

For both charged- and neutral-current, deep-inelastic scattering, the cross sections can be written as (for the case where produced quark masses are negligible):

$$\frac{d^{2}\sigma^{\nu}(i)}{dxdy} = \frac{G^{2}mE}{\pi} F(x) \left[(a_{L}^{i} + b_{L}^{i}) + (a_{R}^{i} + b_{R}^{i})(1-y)^{2} \right] \kappa^{-4}$$
(3.2)

$$\frac{d^{2}\sigma^{\overline{\nu}}(i)}{dxdy} = \frac{G^{2}mE}{\pi} F(x) \left[(a_{L}^{i} + b_{L}^{i})(1-y)^{2} + (a_{R}^{i} + b_{R}^{i}) \right] \kappa^{-4}$$
(3.3)

where i = c (charged-currents) or n (neutral-currents) and where a_L^i and a_R^i (b_L^i and b_R^i) are the left- and right-handed couplings squared of u quarks (d quarks).

 $a_{L,R}^{c}$ and $b_{L,R}^{c}$ are zero when a given process is not allowed. When allowed, $a_{L,R}^{c}$ and $b_{L,R}^{c}$ are equal to 0 for singlets, 1 for doublets, 2 for triplets, etc. (i.e., equal to twice the weak isospin τ^{W}).

The SU(2) × U(1) gauge theory of Weinberg and Salam has neutral currents, $J_{\mu}^{(n)}$, which are found from

$$J_{\mu}^{(n)} = J_{\mu}^{(o)} - 2\sin^2\theta_{W}J_{\mu}^{em}$$
(3.4)

where J_{μ}^{em} is the usual electromagnetic current and $J_{\mu}^{(0)} = C_0 \gamma_{\mu} (1 + \gamma_5)$. The matrix of couplings C_0 can be found from $C_0 = [C, C^{+1}]$ where C is the matrix of charged-current couplings. It then can easily be shown that 23

$$a_{\rm L}^{\rm n} = \frac{1}{4} \left(\alpha_{\rm L} - \frac{4}{3} \sin^2 \theta_{\rm W} \right)^2 \tag{3.5}$$

$$a_{R}^{n} = \frac{1}{4} \left(\alpha_{R} - \frac{4}{3} \sin^{2} \theta_{W} \right)^{2}$$
 (3.6)

$$b_{\rm L}^{\rm n} = \frac{1}{4} \left(\beta_{\rm L} + \frac{2}{3} \sin^2 \theta_{\rm W}\right)^2$$
(3.7)

$$b_{\rm R}^{\rm n} = \frac{1}{4} \left(\beta_{\rm R} + \frac{2}{3} \sin^2 \theta_{\rm W}\right)^2$$
(3.8)

where the factor $\frac{1}{4}$ is an isospin factor. $\alpha_{L,R}$ and $\beta_{L,R}$ are equal to $2\tau_3^W$. Other values of $\alpha_{L,R}$ (or $\beta_{L,R}$) can be obtained if, for example, the u quark mixes with a quark in a singlet ($\alpha_{L,R}$ is then the appropriate fraction of $2\tau_3^W$). In all calculations of neutral currents, uu and dd are kept while s, c and all other terms are ignored. The cross sections for elastic ν_P scattering are not shown here (see Ref. 19).

For the production of a heavy quark (anything but u, d or s) in chargedcurrent scattering, Eqs. (3.2) and (3.3) are poor approximations of the correct formulas.²⁴ For given terms in the charged currents:

$$\frac{d^{2}\sigma^{\nu}, \overline{\nu}}{dx dy} = \frac{G^{2}mE}{\pi} F(z) \left[(a_{L}^{c} + b_{L}^{c}) f_{+, -}(x, z, y) + (a_{R}^{c} + b_{R}^{c}) f_{-, +}(x, z, y) \right] \theta (1 - z)$$
(3.9)

where

$$f_{\pm}(x, z, y) = (1 - y) \pm \frac{x}{z} \left[\frac{y^2}{2} \pm \left(y - \frac{y^2}{2} \right) \right],$$
 (3.10)

$$z = x + \frac{m_q^2}{2m Ey}$$
(3.11)

where m_q is the mass of the produced quark. of course, in the case $m_q \approx 0$, then $z \approx x$, $f_{+}=1$, $f_{-}=(1-y)^2$, and one obtains the original equations (Eqs. (3.2) and (3.3)).

For ν_{μ} elastic scattering off electrons, the cross-sections can be written

as:

$$\frac{d\sigma^{\nu}}{dE_{e}} = \frac{G^{2}m_{e}}{2\pi} \left[d_{L}^{n} + d_{R}^{n} \left(1 - \frac{E_{e}}{E_{\nu}} \right)^{2} - \frac{m_{e}E_{e}}{E_{\nu}^{2}} \left(d_{L}^{n} d_{R}^{n} \right)^{\frac{1}{2}} \right] \kappa^{-4}. \quad (3.12)$$

The factor $(1 - E_e/E_{\nu})^2$ (analogous to $(1 - y)^2$) is moved to d_L^n for antineutrino scattering. In the limit in which the third term goes to zero Eq. (3.12) is completely analogous with Eq. (3.2). However, it is common²³ to express d_L^n and d_R^n as:

$$d_{L}^{n} = (g_{V} + g_{A})^{2} \kappa^{4}$$
 (3.13)

$$d_{\rm R}^{\rm n} = (g_{\rm V} - g_{\rm A})^2 \kappa^4 .$$
 (3.14)

Then clearly

$$g_{V} = \frac{1}{2} \left(\delta_{L} + \delta_{R} + 4 \sin^{2} \theta_{W} \right) \kappa^{-2}$$
(3.15)

$$g_{A} = \frac{1}{2} \left(\delta_{L} - \delta_{R} \right) \kappa^{-2}$$
(3.16)

where (analogously to νN scattering) $\delta_{L,R}$ is equal to $2\tau_3^W$.

For ν_e elastic scattering off electrons, there is an annihilation term (through a W⁻ boson), and Eqs. (3.15) and (3.16) are changed so that $g_V \rightarrow g_V + 1$ and $g_A \rightarrow g_A + 1$ (assuming rule 3). The details of the search for parity-violating neutral-currents in atomic physics are discussed elsewhere^{2,3}, although at present there is still need for more extensive theoretical calculations. However, there is a model-independent term Q_w which can be factored out from the complications of atomic physics (according to Ref. 3 the measured quantity is $2.27 \times 10^{-9} Q_w$ for their experiment). One need only know that the term which is completely dominant is

$$J_{leptonic}^{axial-vector} J_{hadronic}^{vector}$$
 (3.17)

Then since the proton is uud and neutron udd, one can write Q_W as the following product of terms (analogous to g_A and g_V of Eqs. (3.15) and (3.16)):

$$Q_{W} = -\left[(2\alpha_{L}+\beta_{L}+2\alpha_{R}+\beta_{R}-4\sin^{2}\theta_{W})Z + (\alpha_{L}+2\beta_{L}+\alpha_{R}+2\beta_{R})N\right](\delta_{L}-\delta_{R})\kappa^{-2}$$
(3.18)

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

IV. Discussion of Models and Constraints

A brief search for counterexamples can convince one that the following assumptions and data show that ν_{e} and e are in a left-handed doublet (of SU(2)_{weak}): (a) restriction 2 of Section II (μ -e universality), (b) the existence of neutral currents for both ν_{e} and e, (c) the masslessness of ν_{μ} , and (d) the forbidding of $g_{A} = g_{V} = 0$ from $\overline{\nu}_{\mu}$ e scattering. Again using restriction 3 one finds that u and d (and by rule 2 all $-\frac{1}{3}$ charge quarks including s) are in lefthanded doublets. If one wants to cancel triangle anomalies by left-handed versus right-handed currents, there must be, then, at least two right-handed doublets for quarks and for leptons. If the cancellation of anomalies occurs by quarks versus leptons, the choice of any right-handed quark multiplets limits the possible charges of leptons in the corresponding multiplets (and vice versa). The data of constraints 4-6 also severely limit the possible right-handed couplings of quarks and leptons.

The usual Weinberg-Salam-GIM (W-S-GIM) model^{1,5} with four quarks, four leptons and only left-handed currents, is in good agreement with restrictions 1,2,3,5 and 6 (see Fig. 3 and 4). It probably does not explain the chargedcurrent neutrino data¹¹ (constraint 4; see Figs. 1 and 2), but the data⁷⁻¹⁰ is still statistically poor. The model has no heavy lepton and $R(e^+e^-) = 3.33$ (asymptotically), but it also offers a possible explanation of why CP violation is small but finite (see Ref. 25). For $\sin^2 \theta_W = 0.3$, it predicts $Q_W = -143$ (see Table I). If one sacrifices the CP violation scheme of Ref. 25, one can expand this model to six quarks and six leptons, all left-handed. At the present time, one cannot rule out the W-S-GIM model, but it must pass the tests of the charged-current and atomic parity-violation experiments.

The strictly vector model²⁶ with six quarks, six leptons, three lefthanded and three right-handed doublets (and no singlets) satisfies restrictions 1-4 and 6; in Figs. 1 and 2 the short-dashed-curve is appropriate, and in Fig. 4 the line with $g_A = 0$. However, the deep-inelastic, neutral-current data clearly do not appear to be vector, see Fig. 3. Zero parity-violation is predicted for the atomic physics experiments (as elsewhere).

There are three other models (in addition to W-S-GIM) which are in reasonable agreement with most of the data. If one suppresses Cabibbo angles (in notation only), ignores singlets, and defines

$$\begin{pmatrix} u \\ d \end{pmatrix}_{L} \equiv \overline{u} \gamma_{\mu} (1 + \gamma_{5}) d$$
 (4.1)

then the models are:

Model A

$$\begin{pmatrix} u \\ d \end{pmatrix}_{L} \begin{pmatrix} c \\ s \end{pmatrix}_{L} \begin{pmatrix} t \\ d \\ a \end{pmatrix}_{R} \begin{pmatrix} c \\ s \\ v \end{pmatrix}_{R} \qquad \begin{pmatrix} \nu \\ e \\ e \end{pmatrix}_{L} \begin{pmatrix} \nu \\ \mu \\ \mu \end{pmatrix}_{L} \begin{pmatrix} E^{++} \\ E^{0} \end{pmatrix}_{R} \begin{pmatrix} M^{++} \\ M^{+} \\ M^{0} \end{pmatrix}_{R}$$

where a and v quarks have charge $-\frac{4}{3}$ (several minor variations of this model are possible). Model A has identically the neutral currents of the W-S-GIM model (and does not appear separately in Figs. 3 4, and Table I). The antineutrino anomalies occur because of the coupling of d to a quarks. The strength of this charged-current coupling has increased by a factor of $\sqrt{2}$ (relative to that for doublets). This requires a higher mass for the a quark ($m \approx 6.5 \text{ GeV}$) than for doublets ($m \approx 5 \text{ GeV}$). This model, of course, follows the fate of the W-S-GIM model in the atomic physics experiments. As given, there are large charm-changing neutral-currents, but it is not necessary to put c in any righthanded triplet.

Model B^{6,18}

$$\begin{pmatrix} u \\ d \end{pmatrix}_{L} \begin{pmatrix} c \\ s \end{pmatrix}_{L} \begin{pmatrix} d \\ a \end{pmatrix}_{R} \begin{pmatrix} s \\ v \end{pmatrix}_{R} \begin{pmatrix} \nu \\ e \end{pmatrix}_{L} \begin{pmatrix} \nu \\ \mu \end{pmatrix}_{L} \begin{pmatrix} E^{+++} \\ E^{++} \end{pmatrix}_{R} \begin{pmatrix} M^{+++} \\ M^{++} \end{pmatrix}_{R}$$

where a and v quarks have charge $-\frac{4}{3}$ and there are possible variations which allow for an E⁻ lepton. Here it is needed to have $\kappa \approx 1.27$. The chargedcurrent predictions are the same as for $(u, b)_R$ coupling for the same a and b masses. Model B has very mediocre agreement with deep-inelastic, neutralcurrent data, Fig. 3. Rather large positive values for Q_w are predicted (Table I). Model C^{6}

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \mathbf{r} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \mathbf{u} \\ \mathbf{\phi} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} \mathbf{t} \\ \mathbf{d} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} \mathbf{r} \\ \mathbf{\phi} \end{pmatrix}_{\mathbf{R}}$$

where the leptons may be either

(a)
$$\binom{\nu}{e}_{L} \binom{\nu}{\mu}_{L} \binom{\nu}{U}_{U}_{L} = \binom{N}{e}_{R} \binom{N}{\mu}_{R} \binom{N}{U}_{U}_{R}$$

or

(b)
$$\begin{pmatrix} \nu_{\mathbf{e}} \\ \mathbf{e} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \nu_{\boldsymbol{\mu}} \\ \boldsymbol{\mu} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} \nu_{\mathbf{U}} \\ \mathbf{U} \end{pmatrix}_{\mathbf{L}} \begin{pmatrix} N_{\mathbf{E}} \\ \mathbf{E} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} N_{\mathbf{M}} \\ \mathbf{M} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} N_{\mathbf{V}} \\ \mathbf{V} \end{pmatrix}_{\mathbf{R}}.$$

To be different from the vector model, Model C must have large mixing between the right-handed r and u quarks; here equal mixtures are assumed ($\alpha_R = \frac{1}{2}$ in Eq. (3.6) and elsewhere) which requires m(b) ≈ 4 GeV. This model needs $\kappa \approx 1.28$. The fit to deep-inelastic, neutral-current data is not very good, see Fig. 3. If $\alpha_R > \frac{1}{2}$ this fit becomes worse, and if $\alpha_R < \frac{1}{2}$ the charged-current data is poorly fit (see Figs. 1 and 2 for $\alpha_R = \frac{1}{2}$). The values of Q_w predicted are similar to W-S-GIM for possibility (b) and zero for (a).

Models A, B, and C are not very appealing aesthetically, and they plus W-S-GIM could be shown wrong by improved data for neutral- or chargedcurrent scattering and by the atomic, parity-violating experiments. If that were to happen, there would be no remaining models which satisfy the rules of Section II. Higher representations of $SU(2)_{weak}$ (quadruplets, etc.) do not give significantly different models although the couplings grow relative to the left-handed doublets.

If one assumes that all experiments, calculations of scaling violation, and $SU(2) \times U(1)$ are correct, then one could question constraints 1-3. Restriction

1 is a well-accepted assumption which cannot be modified except by elimination. Modification of restriction 3 is possible only by requiring large mixing of a precise amount, aesthetically unappealing. There is not yet good reason for these drastic changes in our beliefs, and models resulting from such changes will not be discussed here. However, it is possible to make a moderate change in constraint 2 (natural GIM) and this will be investigated now. A revised restriction 2 can be stated:

(2') All light (and heavy, separately) quarks of charge $-\frac{1}{3}$ must have the same values of τ_{3L} , of τ_{3R} , or $\overline{\tau}_{L}^{2}$ and of $\overline{\tau}_{R}^{2}$ (separately) where τ is the weak isospin (from SU(2)_{weak}). Furthermore, light quarks of charge $-\frac{1}{3}$ must never mix with heavy quarks.

It is not, at present, possible to show a mechanism which guarantees (even after weak radiative corrections) that light quarks do not mix with heavy quarks. This lack of mixing must be quite exact since there are no strangenesschanging neutral-currents to quite high order. One might speculate that the large mass splitting of the quarks and the lack of mixing are related.

Given the revised constraint 2', there are four Cal Tech²⁷, Harvard²⁸, Yale-Maryland²⁹ (CHYM) models which are minor variations of the same model^{23,30} (although the E_7 model^{27,29} is the result of a proposed unified theory of strong, weak and electromagnetic interactions). Models D, E and F all have the same left-handed couplings as the W-S-GIM model (with the b and g quarks and new leptons in left-handed singlets).

The right-handed quark sectors for D, E and F are

Models D, E, F

$$\begin{pmatrix} u \\ b \end{pmatrix}_{R} \begin{pmatrix} c \\ g \end{pmatrix}_{R} \quad (d)_{R} \quad (s)_{R}$$

while right-handed leptons are

Model D

$$\begin{pmatrix} {}^{N}_{E} \\ {}_{E} \end{pmatrix}_{R} \quad \begin{pmatrix} {}^{N}_{M} \\ {}_{M} \end{pmatrix}_{R}$$

Model E

$$\begin{pmatrix} {}^{N}e \\ e \end{pmatrix}_{R} \begin{pmatrix} {}^{N}\mu \\ \mu \end{pmatrix}_{R}$$

Model F

$$\begin{pmatrix} E^+\\ N\\ e \end{pmatrix}$$
 plus other left- and right-handed parts.

Models E and F are allowed in E_7 . A fourth CHYM model which can have the lepton sectors of models D, E or F is

Model G

$$\begin{pmatrix} \mathbf{u}_{\phi} \\ \mathbf{e} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} \mathbf{c} \\ \mathbf{g} \end{pmatrix}_{\mathbf{R}} \begin{pmatrix} (\mathbf{t}_{\phi})_{\mathbf{R}} \\ (\mathbf{d})_{\mathbf{R}} \end{pmatrix}_{\mathbf{R}}$$

where the u and t quarks mix significantly. Here an equal mixture of u and t is assumed, and the mass of the b quark must be about 4 GeV. Figures 1, 2 and 3 (note the correction mentioned in the figure caption 3) show good agreement with deep-inelastic data for models D-G. For $\nu_{\rm e}$ scattering (Fig. 4) the allowed regions for models D and E contain the same values of $\sin^2 \theta_{\rm W}$ as are required in Fig. 3. However, Model F appears (in Fig. 4) to be in conflict with the present $\overline{\nu}_{\rm e}$ e data. ²¹ Model G depends on which lepton couplings are chosen (as above). In general, these four models (CHYM) are quite consistent with all present data. Note that in Table I that Model G is essentially the only one of the nine models which allows for values of the atomic-parity-violation parameter,

 $|Q_w|$ less than about 100 and greater than zero. There are variations of some above models which have $Q_w = 0$, but intermediate values are difficult to obtain given constraints 1-6 of Section II.

In the next few years, there will be several experiments which will further refine the possible structures of models. The results obtained from atomicparity-violation experiments are crucial. If a zero result is obtained, then one also expects $\sigma(\bar{\nu}_{\mu}e) - \sigma(\nu_{\mu}e) = 0$, since both this difference and Q_w are proportional to $(\delta_L - \delta_R)$. In the continuing study of e^+e^- annihilation, a search for events in which all particles are identified in the processes $e^+e^- \rightarrow D^0\overline{D^0}$ and D^0D^0 (which occurs through mixing) will indicate whether there are charmchanging neutral-currents and thereby expand constraint 2. If such currents exist, then $D^0 - \overline{D^0}$ mixing should be large.

The HPWF and CF experiments⁷⁻⁹ have been done on isoscalar targets, so that the couplings $\overline{u}b$ and $\overline{d}a$ cannot be distinguished; however, if $\overline{\nu}p$ and $\overline{\nu}n$ deepinelastic, charged-current scattering are done, this ambiguity might be removed. If quarks such as the "a" quark with charge $-\frac{4}{3}$ exist, the new PETRA and PEP accelerator experiments will have dramatic results ($R(e^+e^-)$) would increase by 5.33); a "b" quark is more likely to be seen only in a narrow $\overline{b}b$ resonance. These new quarks which are coupled to u or d quarks have mesons $\overline{a}a$ or $\overline{b}b$ whose masses are at lower PETRA and PEP energies.

The newly improved HPWF and CF experiments will in the next year have improved data covering almost all values of y. This will be a great help in resolving the issue of whether charged-current antineutrino scattering has anomalies. In neutral-current scattering, it will minimize the need for modeldependent extrapolations. Their dimuon results should, via p_{\perp} and other distributions, give some indication of the masses of the sources of the second muons. There may be a longer wait to see a resolution of the discrepancy between Gargamelle²⁰ and Aachen-Padua²² ν e data.

It is difficult to draw firm conclusions when there is such great dependence on neutrino experiments with poor statistics and large systematic errors. Certainly there is no compelling reason yet to abandon the pioneering W-S-GIM models, which has successfully predicted so much of the present data. However, if the charged-current, neutrino-scattering data are verified, then one must either reexamine scaling violations, seek models such as those above, question the conventional, theoretical assumptions of Section II, or abandon $SU(2) \times U(1)$. As more and more experiments reach fruition, it remains important in judging models to consider not one type of experiment in isolation but all available and relevant data together.

Acknowledgements

I would like to express my gratitude for valuable conversations to B. W. Lee (including the suggestion to look for models with both doublets and triplets), P. Ramond, P. Sikivie and S. Weinberg. I am thankful for useful conversations with J. Bjorken, R, Cahn, L. N. Chang, S. Ellis, H. Georgi, S. Glashow, E. Golowich, F. Gürsey, T. Hagiwara, K. Lane, H. I. Miettinen, R. Shrock, R. Slansky and W.-K. Tung. The hospitality of the Aspen Center for Physics and the theory group at Fermilab are greatly appreciated.

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Figure Captions

- 1. The ratio of antineutrino to neutrino charged-current cross sections versus incoming lab energy. The solid (dotted) curve is the prediction of the W-S-GIM model with (without) asymptotic freedom (AF) corrections. The short-dashed, long-dashed, and dot-dashed curves are the AF corrected predictions of models with right-handed ub or da couplings for a doublet (a or b mass = 5 GeV), a triplet (a or b mass = 6.5 GeV) and a mixed doublet (see Models C and G; a or b mass = 4 GeV; $\alpha_{\rm R} = 0.5$) respectively. Round points are HPWF data⁷ and square points CF data⁹. The HPWF data and the predictions have two cuts, $E_{\mu} > 4$ GeV and $\theta_{\mu} < 0.225$ radians, and both have been corrected by calculating the fraction of cross sections missed if there were 6% sea (and no new phenomena) independent of energy.
- 2. The average value of y for antineutrino scattering versus incoming lab energy. The solid (dotted) curve is the predictions of the W-S-GIM model with (without) asymptotic freedom (AF) corrections. The short-dashed, long-dashed and dot-dashed curves are the AF corrected predictions of models with right-handed ub or da couplings for a doublet (a or b mass = 5 GeV), a triplet (a or b mass = 6.5 GeV), and a mixed doublet (see Models C and G; a or b mass = 4 GeV; $\alpha_{\rm R}$ = 0.5) respectively. The points are HPWF data⁸. The data and the predictions have the following cuts: a) $E_{\mu} > 4$ GeV, b) $\theta_{\mu} < 0.225$ radians, c) x < 0.6 and d) Q² > 1.0 GeV or W > 1.6 GeV (no corrections are made).
- 3. The ratio $\sigma (\nu N \nu + X) / \sigma (\nu N \mu + X)$ for antineutrinos versus that ratio for neutrinos. The three solid curves are the predictions of the W-S-GIM, vector and CHYM (D, E and F) models as a function of $\sin^2 \theta_W$ where tenth

values of $\sin^2 \theta_W$ are shown with tick marks. The dashed, dot-dashed and dotted curves are predictions for models B, C and G (with $\alpha_R = 0.5$) respectively. The predictions always assume $\sigma (\nu N \rightarrow \mu + X)$ is due to $(u, d)_L$ only (no sea and no new phenomena). As a result, to make fair comparisons, the Gargamelle¹⁴, HPWF¹², and CF¹³ data for $R_{\overline{\nu}}$ can be increased by about 14%, 33% and 40% respectively, to account for their reported charged-current ratios. The antineutrino neutral-current data of HPWF has been corrected by a model-dependent extrapolation into unseen y regions; for the models here then results are between the two points shown. Similar extrapolations could (they would lower $R_{\overline{\nu}}$ slightly) but have not been done to Gargamelle and CF data.

4. The limits placed on g_A and g_V by νe scattering. The solid (long-dashed) curves show the upper and lower limits (90% confidence) imposed from $\overline{\nu}_{\mu} e \ data^{20} \ (\overline{\nu}_e e \ data^{21})$. The short-dashed curves show the upper limit (90% confidence) from $\nu_{\mu} e \ data$.²⁰ The shaded region is the overlap area, presumably the allowed region. Assuming $\beta_e = -2$ (Model F), -1 (Models C(a), E and vector) and 0 (Models A, B, C(b), D and W-S-GIM) respectively. The dots on these lines indicate tenths of $\sin^2 \theta_W$. Model dependent corrections to $\overline{\nu}_{\mu} e$ scattering tend to favor the upper limits.

Table I

The parity-violation-parameter Q_w for weak-neutral-current transitions in atomic physics experiments, as a function of $\sin^2 \theta_W$. All models have $\kappa = 1$ except for B ($\kappa = 1.27$) and C ($\kappa = 1.28$). Model C(a) has $Q_w = 0$ for all $\sin^2 \theta_W$. Model A is the same as W-S-GIM.

$\sqrt{\sin^2\theta_W}$						
Model	0.0	0.1	0.2	0.3	0.4	0.5
W-S-GIM			- 109	- 143	- 176	- 209
Vector	0	0	0	0	0	0
в	+ 181	+161	+ 140	+ 119		-
C(b)	- 142	- 162	- 182	- 203		
D			+ 183	+ 149	+ 116	+ 83
\mathbf{E}	0	0	0	0	0	0
F			- 183	- 149	- 116	- 83
G			+ 37	+ 3	- 30	- 63
				1	1	



Fig. 1



Fig. 2



Fig. 3



Fig. 4