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NEUTRAL CURRENT PHENOMENOLOGY BASED ON THE GAUGE GROUP SU(2) X U(1) X U'(1) *

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ABSTRACT

We construct models based on the gauge group SU(2) X U(1) X U'(1) as alternatives to the standard model. These lead naturally to effective Lagrangian for the neutrino-hadron scattering which is identical to the standard model. The electron-quark interactions can be chosen to yield the correct result for polarized electron-deuterium asymmetry measured at SLAC, while permitting a small value for parity violation in bismuth. Definitive tests for these models are the y-dependence of the asymmetry in electron-deuterium and electron-proton deep inelastic scattering, which should be fairly rapid, and the assignment of e_R to a doublet which can be tested on neutrino-electron scattering. Other tests of the models are also considered. A different version of the model predicts all results identical to the standard model at small q^2, but allowing a lighter Z-boson. Models which are not strictly natural are also discussed.

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1. Introduction

Recent model independent analysis [1] of neutrino-hadron neutral current data confirms the standard SU(2) X U(1) gauge model of Weinberg-Salam (W-S) [2] with the Glashow-Iliopoulos-Maiani [3] mechanism. The situation with the neutrino-electron scattering and the electron-hadron scattering data is not as clear, however. Recent observation of asymmetry in polarized electron-deuterium scattering at SLAC [4] tends to confirm W-S model. However, the lack of large enough parity nonconservation signal in experiments on bismuth at Seattle [5] and at Oxford [6] is a matter of deep concern. A larger result observed at Novosibirsk [7] may mean that there are unknown experimental difficulties, or the atomic theory for bismuth might not be very well understood. On the other hand, the possibility remains that W-S model accounts only for the ν-hadron processes, while the model needs a modification to satisfactorily explain these other effects.

We already know that within SU(2) X U(1) group any change in the assignment of left-handed fermions to doublets and the right-handed fermions to singlets would contradict the experiment. In particular, the hybrid model [8] which assigns e_R to a doublet is consistent with ν-e data and atomic physics experiments on bismuth, but inconsistent with the observed asymmetry in electron-hadron scattering. Further, the charged currents are consistent with W-S model. Thus the simplest group that can lead to a theory of ν-hadron scattering identical to W-S model [9], and permitting departure in electron interactions, is the group SU(2) X U(1) X U'(1). This model has been extensively studied in the literature [10] with a view of making neutral currents parity conserving. With the observation of asymmetry in e-d scattering, all these models are ruled out with the exception of a model due to Ma, Pramudita and Tuan (MPT) [11] which we shall consider in detail later. Throughout most of this paper we shall enforce a criterion of naturalness of

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the model. By this we mean that the model should yield predictions for ν-hadron interactions identical to W-S model naturally, and not by adjusting some set of coupling constants. In this sense the MPT model is not strictly natural.

In Sect. 2 we establish a notation for model independent analysis of the experimental situation, and discuss the present data. In Sect. 3 we present a general formulation of the SU(2) X U(1) X U'(1) group and present the criteria for naturalness of the models. In Sect. 4 two different natural models are discussed*. Detailed tests for these models are presented. In Sect. 5 we discuss models where the criterion of naturalness is relaxed. Our conclusions are summarized in Sect. 6.

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*A preliminary version of our results appears in a brief paper, "Gauge Models and Neutral Currents," University of Oregon preprint OITS-101, to be published.

2. Phenomenology of Electron Interactions and Data

2.1. Electron-neutrino interactions

The effective interactions of electrons with neutrinos due to neutral currents arising in any gauge model may be written as

$$\mathcal{L}_{e-\nu} = -(G_F/\sqrt{2})(\bar{\nu}\gamma^{\mu}(1+\gamma_5)\nu)(\bar{e}\gamma_{\mu}(g_V+g_A\gamma_5)e) \quad , \qquad (2.1)$$

where we have assumed μ-e universality. The experiments are based on left-handed neutrinos produced in charged interactions and thus the presence of right-handed neutrino interactions is not detectable at present; consequently we have ignored these in Eq. (2.1). Our knowledge of g_V and g_A comes from ν_μ and $\bar{\nu}_\mu$ scattering on electrons [12] and scattering of $\bar{\nu}_e$ from reactors [13]. The data is still not sufficiently good to give a definite prediction for g_V and g_A, but two possible solutions emerge [14], solution A:

$$g_V = -.03 \pm .12 \qquad g_A = -.52 \pm .15 \qquad (2.2)$$

and solution B:

$$g_A = -.03 \pm .12 \qquad g_V = -.52 \pm .15 \qquad (2.3)$$

Solution A agrees with W-S model with $X \equiv \sin^2\theta_W \sim .25$, while solution B would agree with the hybrid model for the same value of X. The theoretical expressions for these couplings in SU(2) X U(1) are

$$2g_V = 4X-1-D$$
$$2g_A = D-1 \qquad (2.4)$$

where D = 0 corresponds to e_R in singlet representation (W-S model), and D = 1 corresponds to e_R in a doublet representation (hybrid model). In a natural model based on SU(2) X U(1) X U'(1), neutrino scattering is identical to SU(2) X U(1) model. Thus we shall obtain the same result as in Eq. (2.4) and we leave open the option of the assignment of e_R to a singlet or to a doublet.

2.2 Electron-hadron interactions

The effective parity nonconserving part of electron-quark interaction that arises from the exchange of weak neutral bosons can be parameterized as [15]

$$\mathcal{L}_{e-q} = +(G_F/\sqrt{2})\Big[\bar{e}\gamma^{\mu}e\left(\varepsilon_{VA}(e,u)\,\bar{u}\gamma_{\mu}\gamma_5 u + \varepsilon_{VA}(e,d)\,\bar{d}\gamma_{\mu}\gamma_5 d\right) + \bar{e}\gamma^{\mu}\gamma_5 e\left(\varepsilon_{AV}(e,u)\,\bar{u}\gamma_{\mu}u + \varepsilon_{AV}(e,d)\,\bar{d}\gamma_{\mu}d\right)\Big] \tag{2.5}$$

Various polarized electron-hadron scattering experiments as well as parity nonconservation signal in atoms could be used to determine the four unknown constants in Eq. (2.5). The expected asymmetry has been analyzed by Cahn and Gilman [16] for SU(2) X U(1) models where one Z boson exchange was assumed. It is fairly straightforward to generalize these to the model independent form in Eq. (2.5). We present these formulae below. For deep inelastic scattering on a general hadronic target, the asymmetry is given by

$$\frac{A}{Q^2} = -\frac{G_F}{2\sqrt{2}\,\pi\alpha}\;\frac{\sum_i f_i(x)Q_i\left[\varepsilon_{AV}(e,q_i) + f(y)\,\varepsilon_{VA}(e,q_i)\right]}{\sum_i f_i(x)Q_i^2} \tag{2.6}$$

where $A \equiv (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$, $f_i(x)$ is the structure function of quark of type q_i, and Q_i is the charge measured in units of $|e|$. The function $f(y)$ is $[1-(1-y)^2]/[1+(1-y)^2]$ where $y = (E_e - E'_e)/E_e$.

a. Electron-deuterium deep inelastic scattering

Here $f_u(x) = f_d(x)$ for $x > .1$, and x dependence drops out, and we obtain

$$\frac{A^{ed}}{Q^2} = -\frac{3G_F}{10\sqrt{2}\,\pi\alpha}\Big[\left(2\varepsilon_{AV}(e,u) - \varepsilon_{AV}(e,d)\right) + f(y)\left(2\varepsilon_{VA}(e,u) - \varepsilon_{VA}(e,d)\right)\Big] \tag{2.7}$$

The recent measurement $A^{ed}/Q^2 = -(9.5 \pm 1.6) \times 10^{-5}$ at $y \approx .21$ then leads to the constraint

$$0.89 \pm 0.15 = \left[2\varepsilon_{AV}(e,u) - \varepsilon_{AV}(e,d)\right] + 0.23\left[2\varepsilon_{VA}(e,u) - \varepsilon_{VA}(e,d)\right] \tag{2.8}$$

b. Electron-proton deep inelastic scattering

The formula in general depends on the ratio $r = f_u(x)/f_d(x)$. This ratio can be determined from e-p and e-d deep inelastic scattering. We find

$$\frac{A^{ep}}{Q^2} = -\frac{3G_F}{2\sqrt{2}\,\pi\alpha(4r+1)}\Big[\left(2r\,\varepsilon_{AV}(e,u) - \varepsilon_{AV}(e,d)\right) + f(y)\left(2r\,\varepsilon_{VA}(e,u) - \varepsilon_{VA}(e,d)\right)\Big] \tag{2.9}$$

for small x ($x \approx .15$) where the experiment was carried out, $r \approx 1$ and the formula is identical to Eq. (2.7). However, for $.3 < x < .6$, $r \approx 2$ and different combinations of couplings can be measured.

c. Electron-proton elastic scattering

Following quark model assumptions made in [16], we find

$$\frac{A^{ep}_{el}}{Q^2} = -\frac{G_F}{2\sqrt{2}\,\pi\alpha}\;\frac{\left[2\varepsilon_{AV}(e,u) + \varepsilon_{AV}(e,d)\right] + \frac{Q^2}{4M^2}\mu_p\left[\varepsilon_{VA}(e,u)(2\mu_p + \mu_n) + \varepsilon_{AV}(e,d)(\mu_p + 2\mu_n)\right]}{1 + \frac{Q^2}{4M^2}\mu_p^2} \tag{2.10}$$

d. $e + p \to e + \Delta^{+}(1236)$

$$\frac{A^{ep\to e\Delta}}{Q^2} = -\frac{G_F}{2\sqrt{2}\,\pi\alpha}\left[\mathcal{E}_{AV}(e,u) - \mathcal{E}_{AV}(e,d)\right] \tag{2.11}$$

e. Electron-deuterium elastic scattering [17]

$$\frac{A^{ed}_{el}}{Q^2} = -\frac{G_F}{\pi\alpha\sqrt{2}}\,\frac{3}{2}\left[\mathcal{E}_{AV}(e,u) + \mathcal{E}_{AV}(e,d)\right] \tag{2.12}$$

The above measurement can give unambiguously the four unknown coupling constants. Further, atomic physics experiments on heavy atoms measure a quantity Q_W defined by

$$Q_W = 2(2Z+N)\left[\mathcal{E}_{AV}(e,u) + \left(\frac{Z+2N}{2Z+N}\right)\mathcal{E}_{AV}(e,d)\right] \tag{2.13}$$

For bismuth this is

$$Q_W^{Bi} = 584\left[\mathcal{E}_{AV}(e,u) + 1.15\,\mathcal{E}_{AV}(e,d)\right] \tag{2.14}$$

The present experiments on bismuth have generally led to smaller values of Q_W than predicted by W-S model. The data are summarized in [5], [6], [7].

$$\begin{aligned} |Q_W| &< 20 && \text{(Seattle)} \\ Q_W &= -34 \pm 7 && \text{(Oxford)} \\ Q_W &= -120 \pm 40 && \text{(Novosibirsk)} \end{aligned} \tag{2.15}$$

Work on Thallium [17] is in progress and should yield invaluable data.

3. Gauge Group SU(2) X U (1) X U'(1)

In this section we present a general analysis of the group SU(2) X U(1) X U'(1) and show how natural models can be built. The specific models are discussed in Sects. 4 and 5. The analysis is based partly on the work of Ross and Weiler [19].

We associate gauge fields $\vec{W}_\mu$, B_μ and C_μ respectively with groups SU(2), U(1) and U'(1). The associated couplings are g, g' and g'', and the generators $\vec{T}$, Y and Y'. We choose our basis quite generally so that the charge Q is defined by

$$Q = T_3 + Y \tag{3.1}$$

The gauge fields acquire mass by spontaneous breakdown of symmetry. The Higgs structure is constrained to arbitrary number of doublets $\Phi_i \equiv (\phi_i^+, \phi_i^0)$ and complex singlets ψ_i. This will insure that the strength of the neutral currents are normalized to the charged currents as in W-S model. The mass matrix is given by

$$\frac{1}{2}\left|\left(g\,\frac{\vec{T}}{2}\cdot\vec{W}_\mu + g'YB_\mu + g''Y'C_\mu\right)\left(\Phi_i \text{ or } \psi_i\right)\right|^2 \tag{3.2}$$

If the vacuum expectation values are $\langle\Phi_i\rangle = (0, \lambda_i)$ and $\langle\psi_i\rangle = \lambda_i'$, and the fields Z_μ (corresponds to Z boson of W-S) and A_μ (photon) are defined as

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2+g'^2}}, \tag{3.3}$$

$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2+g'^2}}, \tag{3.4}$$

we then have the mass matrix for fields Z and C given by

$$M^2 = \begin{pmatrix} M_Z^2 & M_{ZC}^2 \\ M_{ZC}^2 & M_C^2 \end{pmatrix} \tag{3.5}$$

We further define $\tan\theta_W = g'/g$ as in W-S model. We then find

$$M_Z^2 = \frac{(g^2+g'^2)}{4}\sum_i \lambda_i^2 = \frac{M_{W+}^2}{\cos^2\theta_W},$$

$$M_{ZC}^2 = -\frac{g''\sqrt{g^2+g'^2}}{2}\sum_i y_i'\lambda_i^2,$$

$$M_C^2 = g''^2\left[\sum_i (y_i'\lambda_i)^2 + \sum_j (y_j'\lambda_j')^2\right]. \tag{3.6}$$

The Lagrangian for the neutral currents in terms of the (undiagonalized) fields Z_μ and C_μ is given by

$$\mathcal{L} = \sqrt{g^2+g'^2}\,J_\mu^Z Z^\mu + g'' J_\mu^{Y'} C^\mu \tag{3.7}$$

where J_μ^Z is the usual W-S neutral current

$$J_\mu^Z = J_\mu^3 - X J_\mu^{em} \tag{3.8}$$

with $X = \sin^2\theta_W$ and $J_\mu^{Y'}$ is the current of U'(1) group. At small q^2, assuming that the diagonalized masses M_{Z_1} and $M_{Z_2} \gg q^2$, we obtain an effective Lagrangian

$$\mathcal{L}_{eff} = \left(\sqrt{g^2+g'^2}\,J_\mu^Z,\ g''J_\mu^{Y'}\right)(M^2)^{-1}\begin{pmatrix}\sqrt{g^2+g'^2}\,J_\mu^Z \\ g''J_\mu^{Y'}\end{pmatrix} \tag{3.9}$$

We can write it in a simpler form

$$\mathcal{L}_{eff} = -\frac{8G_F}{\sqrt{2}}\left[J_\mu^Z J^{\mu Z} + \alpha^2\left(J_\mu^Z + J_\mu^{Y''}\right)\left(J^{\mu Z} + J^{\mu Y''}\right)\right] \tag{3.10}$$

where $G_F/\sqrt{2} = (g^2/8M_{W+}^2)$, and

$$\alpha^2 = \frac{M_{CZ}^4}{(\det M^2)} \tag{3.11}$$

$$J_\mu^{Y''} = -\frac{g''}{\sqrt{g^2+g'^2}}\,\frac{M_Z^2}{M_{CZ}^2}\,J_\mu^{Y'} \tag{3.12}$$

The condition that ν-hadron data agree with SU(2) X U(1) model at small q^2 is that the second term in Eq. (3.10) not involve ν_L. A trivial possibility is that $g'' \to 0$. Two nontrivial possibilities remain. If $\alpha^2 \neq 0$, then the condition is that $J_\mu^Z + J_\mu^{Y''}$ not contain ν_L. From Eq. (3.8) we therefore require that Y'' ($\equiv \int J_o^{Y''} d^3X$) quantum number of ν_L satisfies

$$Y''(\nu_L) = -\frac{1}{2} \tag{3.13}$$

Since Eq. (3.12) can be simplified to

$$Y'' = \frac{\sum_i \lambda_i^2}{2\sum_i Y_i'\lambda_i^2}\,Y' \tag{3.14}$$

we see that condition (3.12) can be implemented <u>naturally</u> provided all the Higgs doublets satisfy

$$Y'(\nu_L) = -Y'(\Phi_i) \tag{3.15}$$

We present a natural model based on this condition in the next section.

The second possibility is to require

$$M_{ZC} = 0 \tag{3.16}$$

Then Eq. (3.9) reduces to

$$\mathcal{L}_{eff} = -\frac{8G_F}{\sqrt{2}}\left[J^Z_\mu J^{\mu Z} + \frac{g''^2 M_Z^2}{(g^2+g'^2)M_C^2} J^{Y'}_\mu J^{\mu Y'}\right] \tag{3.17}$$

Now if $Y'(\nu_L) = 0$, we shall recover the standard result for ν-hadron scattering. However, the condition in Eq. (3.16) can be satisfied naturally only if [9]

$$Y'(\Phi_i) = 0 \tag{3.18}$$

Models based on this requirement turn out to be inconsistent with data as discussed in Sect. 4. If the criterion of naturalness is somewhat relaxed, Eq. (3.15) can be satisfied with two Higgs doublets such that

$$Y'(\Phi_1) = -Y'(\Phi_2)$$
$$\lambda_1^2 = \lambda_2^2 \tag{3.19}$$

Condition (3.19) can be realized only at the tree level by imposing a symmetry $\Phi_1 \rightleftarrows \Phi_2$ on the Higgs potential [11]. We do not find this possibility theoretically as attractive, but we discuss models based on this in Sect. 5.

4. Natural Models

We first investigate models with arbitrary Z-C mixing, characterized by $Y'(\nu_L) = -Y'(\Phi_i) \neq 0$. It is sufficient to determine Y'' quantum numbers of various quark and lepton fields. The left-handed quarks are in SU(2) doublets, and ν-hadron data requires right-handed quarks to be in SU(2) singlets. In order to generate masses with Higgs doublets that have $Y''(\Phi_i) = 1/2$, we require the following assignments.

$$Y''(\nu_L, e_L) = -\frac{1}{2}, \quad Y''(e_R) = \gamma, \quad Y''(u_L, d_L) = \beta,$$
$$Y''(u_R) = \beta + \frac{1}{2}, \quad Y''(d_R) = \beta - \frac{1}{2}. \tag{4.1}$$

Where $\gamma = -1$ if e_R is in a singlet, and γ can be arbitrary if e_R is in a doublet; and β is an arbitrary parameter to be determined later. The effective coupling constants defined in Eq. 2.5 can then be readily computed to be

$$g_V = -\frac{(1+D)}{2} + 2X, \quad g_A = \frac{D-1}{2},$$

$$\varepsilon_{VA}(e,u) = -\varepsilon_{VA}(e,d) = \frac{(1+D-4X)}{2},$$

$$\varepsilon_{AV}(e,u) = \frac{(1-D)}{2}\left[1 - \frac{8X}{3}\right] + 4\alpha^2 D\left(\gamma+\frac{1}{2}\right)\left(\beta+\frac{1}{2}-\frac{2X}{3}\right), \tag{4.2}$$

$$\varepsilon_{AV}(e,d) = -\frac{(1-D)}{2}\left[1 - \frac{4X}{3}\right] + 4\alpha^2 D\left(\gamma+\frac{1}{2}\right)\left(\beta-\frac{1}{2}+\frac{X}{3}\right),$$

with $D = \begin{cases} 0 & (e_R \text{ in singlet}) \\ 1 & (e_R \text{ in doublet}) \end{cases}$.

We consider the possibilities.

(a) Case I: e_R is a singlet. All the above couplings agree with W-S model. The only difference is that there are two Z bosons, Z_1 and Z_2, one of which is lighter than W-S value of $M_z = [\alpha\pi/\sqrt{2}\, G_F\, x(1-x)]^{1/2} \simeq 93$ Gev if x = .20. The theory deviates from W-S model at values of q^2 comparable to the lower mass Z boson.

(b) Case II: e_R is in a doublet. We reach the following conclusions:

(i) The vector dominant (B) solution is preferred over the W-S axial dominant (A) solution in ν-e scattering.

(ii) The polarized electron-hadron deep inelastic scattering should exhibit a strong y dependence. We write the expressions for asymmetries for different processes below:

(a) Electron-deuterium deep inelastic scattering

$$\frac{A^{ed}}{Q^2} = -1.08 \times 10^{-4} \left[\lambda\left(\beta + \tfrac{3}{2} - \tfrac{5x}{3}\right) + f(y)\,(3-6x)\right] \tag{4.3}$$

where $\lambda = 4\alpha^2(\gamma + \frac{1}{2})$. The recent measurement of $A/Q^2 = -(9.5 \pm 1.6) \times 10^{-5}$ then requires

$$\lambda\left(\beta + \tfrac{3}{2} - \tfrac{5x}{3}\right) = 0.545 \pm 0.15 \tag{4.4}$$

For x = .25 the coefficient of f(y) is 1.5. This would give a dramatic y dependence. We have plotted these curves in Fig. 1.

(b) Electron-proton deep inelastic scattering

For small x the expression is identical to Eq. 4.3. For x = .3∼.6, we obtain

$$\frac{A^{ep}}{Q^2} = -1.08 \times 10^{-4} \times \frac{25}{27} \left[\lambda\left(\frac{9\beta}{5} + \frac{3}{2} - \frac{9x}{5}\right) + f(y)\,(3-6x)\right] \tag{4.5}$$

This is also very similar to Eq. (4.3) and predicts a rapid y dependence of the asymmetry for small values of β .

(c) Electron-proton elastic scattering

$$\frac{A^{ep}_{el}}{Q^2} = -9.0 \times 10^{-5} \lambda \left[\frac{(6\beta+1-2x) + \frac{Q^2}{4M^2}\mu_p\left[(6\beta+1-2x)\mu_p + (6\beta-1)\mu_N\right]}{1 + \frac{Q^2}{4M^2}\mu_p^2}\right] \tag{4.6}$$

(d) $e + p \rightarrow e + \Delta^+$ (1236)

$$\frac{A^{ep\rightarrow e\Delta^+}}{Q^2} = -18.0 \times 10^{-5} \lambda (1-x) \tag{4.7}$$

(e) Electron-deuterium elastic scattering

$$\frac{A^{ed}_{el}}{Q^2} = -18.0 \times 10^{-5} \lambda (6\beta - x) \tag{4.8}$$

(iii) For Q_W we find the expression

$$Q_W = 2(2Z+N)\lambda\left[\left(\beta + \tfrac{1}{2} - \tfrac{2x}{3}\right) + \frac{(2N+Z)}{(2Z+N)}\left(\beta - \tfrac{1}{2} + \tfrac{x}{3}\right)\right] \tag{4.9}$$

For bismuth this reduces to

$$Q_W^{Bi} = 584\lambda\,[2.15\beta - 0.075 - 1.28x] \tag{4.10}$$

Although the two parameters β and λ can be determined experimentally, an attractive theoretical possibility is that β = 0. The asymmetry in electron-deuterium scattering then fixes λ . We find the following solution:

$$\beta = 0 \quad , \quad \lambda = 0.503 \pm 0.139 \; ,$$

$$Q_W = -43 \pm 11 \; . \tag{4.11}$$

This value of Q_W is consistent with Oxford data.
All the asymmetries are then determined and we have shown these in Fig. 1 through 4, where comparison is made with W-S model.

If in future experiments a larger parity violation is found in atoms, the value of β can be chosen appropriately. The one characteristic prediction of this model is that the asymmetries in e-d and e-p deep inelastic scattering exhibit a characteristic rapid y dependence.

We now turn to natural models constructed by requiring

$$y'(\Phi_i) = y'(\nu_L, e_L) = 0 \tag{4.12}$$

In this case the effective Lagrangian is

$$\mathcal{L}_{eff} = -\frac{8G_F}{\sqrt{2}}\left[J^z_\mu J^{\mu z} + \tilde{\alpha}^2 J^{y'}_\mu J^{\mu y'} \right] \tag{4.13}$$

where $\tilde{\alpha}^2 = \left(M_Z^2 \, g^{o2} / M_C^2 (g^2 + g'^2) \right)$. The other quantum numbers are

$$y'(u_L, u_R, d_L, d_R) = \beta \quad , \quad y'(e_R) = \gamma \tag{4.14}$$

where $\gamma = 0$ if e_R is in the singlet, and arbitrary otherwise.

The coupling constants are then found to be

$$g_V = -\frac{(1+D)}{2} + 2X \quad , \quad g_A = \frac{D-1}{2} \; ,$$

$$\varepsilon_{VA}(e,u) = -\varepsilon_{VA}(e,d) = \frac{(1+D-4X)}{2} \; ,$$

$$\varepsilon_{AV}(e,u) = \frac{(1-D)}{2}\left(1 - \frac{8X}{3}\right) + 4\tilde{\alpha}^2 \gamma\beta \; , \tag{4.15}$$

$$\varepsilon_{AV}(e,d) = -\frac{(1-D)}{2}\left(1 - \frac{4X}{3}\right) + 4\tilde{\alpha}^2 \gamma\beta \; .$$

As before, if e_R is a singlet ($D = 0$) we see that the expressions are identical to the W-S model. If e_R is in a doublet, the asymmetry in polarized electron-deuterium has strong y dependence:

$$\frac{A^{ed}}{Q^2} = -1.08 \times 10^{-4}\left[4\tilde{\alpha}^2 \gamma\beta + f(y)(3 - 6X) \right] \tag{4.16}$$

However, now Q_W for bismuth comes out to be

$$Q_W = 584\left[2.15 \times 4\tilde{\alpha}^2 \gamma\beta \right] = 684 \pm 155 \tag{4.17}$$

This value is very large and has opposite sign to W-S model. Thus this model is not acceptable.

5. Other Models

We examine here models based on two Higgs doublets that satisfy $Y'(\Phi_1) = -Y'(\Phi_2) = 1$ and $\lambda_1^2 = \lambda_2^2$. This requirement leads to $M_{ZC} = 0$ and the effective Lagrangian is

$$\mathcal{L}_{eff} = -\frac{8G_F}{\sqrt{2}}\left[J_\mu^z J^{\mu z} + \tilde{\alpha}^2 J_\mu^{y'} J^{\mu y'}\right] \tag{5.1}$$

We can assign Y' quantum numbers as follows:

$$\begin{aligned} &y'(\nu_L, e_L) = 0\ ,\ y'(e_R) = \gamma\ ,\ \ y'(u_L, d_L) = \beta\ , \\ &y'(u_R) = \beta + \eta\ ,\ \ y'(d_R) = \beta + \xi \end{aligned} \tag{5.2}$$

where $|\eta| = 1$ and $|\xi| = 1$. The coupling constants g_V and g_A are as before. The other couplings are

$$\begin{aligned} 2\,\varepsilon_{VA}(e,u) &= (1+D-4x) + 4\tilde{\alpha}^2\gamma\eta\ , \\ 2\,\varepsilon_{VA}(e,d) &= -(1+D-4x) + 4\tilde{\alpha}^2\gamma\xi\ , \\ 2\,\varepsilon_{AV}(e,u) &= (1-D)\left(1-\frac{8x}{3}\right) + 4\tilde{\alpha}^2\gamma(2\beta+\eta)\ , \\ 2\,\varepsilon_{AV}(e,d) &= -(1-D)\left(1-\frac{4x}{3}\right) + 4\tilde{\alpha}^2\gamma(2\beta+\xi)\ . \end{aligned} \tag{5.3}$$

We now find the following two possibilities.

Case I: e_R is a singlet: Our conclusions for this case are: (i) axial dominant e-ν scattering is obtained as in W-S model. (ii) The asymmetry in electron-deuterium scattering is given by

$$\frac{A^{ed}}{Q^2} = -1.08\times 10^{-4}\Big[\left(\tfrac{3}{2}-\tfrac{10x}{3}\right) + 2\tilde{\alpha}^2\gamma(2\beta+2\eta-\xi) + f(y)\left(\tfrac{3}{2}(1-4x) + 2\tilde{\alpha}^2\gamma(2\eta-\xi)\right)\Big] \tag{5.4}$$

while (iii) Q_W for bismuth is given by

$$Q_W^{Bi} = \frac{584}{2}\left[-0.15 - 1.13x + 4\tilde{\alpha}^2\gamma(4.3\beta+\eta+1.15\xi)\right] \tag{5.5}$$

A possible solution is $(2\beta + 2\eta - \xi) = 0$ and $\xi = -\eta = 1$. Then if $Q_W \approx 0$, we obtain

$$2\tilde{\alpha}^2\gamma = .032\ ,\quad \beta = 3/2 \tag{5.6}$$

There is hardly any difference between W-S theory and this theory for e-d or e-p deep inelastic scattering. However, for elastic electron-deuterium scattering we find

$$A^{ed\ elastic}/Q^2 = -1.35\times 10^{-5} \tag{5.7}$$

Compared to W-S value of (x = .25)

$$[A^{ed}/Q^2]_{W-S} = +9\times 10^{-5} \tag{5.8}$$

A large difference can also be obtained for e-p elastic scattering. At small Q^2 we have

$$A^{ep\ elastic}/Q^2 = 5\times 10^{-5} \tag{5.9}$$

Compared to W-S value of (x = .2)

$$[A^{ep\ elastic}/Q^2]_{W-S} = 1.8\times 10^{-5} \tag{5.10}$$

Thus further experiments should reveal if this model is realized by nature.

Case II: e_R is in a doublet: A model based on this assignment was considered by MPT. They chose coupling constants for the special case $\beta = 0$, $\eta = 1$ and $\xi = -1$. The consequences of this model are

(i) vector dominant solution B is preferred for νe scattering;

(ii) for various asymmetries one finds:

(a) Electron-deuterium inelastic scattering

$$\frac{A^{ed}}{Q^2} = -32\times 10^{-5}\left[\delta + f(y)\,(1-2x+\delta)\right] \tag{5.11}$$

where $\delta = 2\alpha^2\gamma$. From observed value of $A^{ed}/Q^2 = 9.5 \pm 1.6$ at $y \approx .21$, and assuming $x = .25$, the value of $\delta = .15 \pm .04$. The asymmetry should have a much stronger y dependence than the natural model, as can be seen by comparing Eq. (5.11) with Eq. (4.3).

(b) Electron-proton inelastic scattering

For small x this is identical to Eq.(5.11). At higher x, $.3 < x < .6$, we have

$$\frac{A^{ep}}{Q^2} = \frac{25}{27}\,A^{ed} \tag{5.12}$$

(c) Electron-proton elastic scattering

$$\frac{A^{ep}_{el}}{Q^2} = -17.8\times 10^{-5}\times(0.15 \pm 0.04)\left[\frac{1+\frac{Q^2}{4M^2}\mu_p(\mu_p-\mu_N)}{1+\frac{Q^2}{4M^2}\mu_p^2}\right] \tag{5.13}$$

(d) Electron + proton → electron + $\Delta^+(1236)$

$$\frac{A^{ep\to e\Delta^+}}{Q^2} = -35.5\times 10^{-5}(0.15 \pm 0.04) \tag{5.14}$$

(e) Electron-deuterium elastic scattering

$$A^{ed\ \mathrm{elastic}}/Q^2 = 0 \tag{5.15}$$

(iii) The value of Q_W for bismuth turns out to be

$$Q_W = 584\left[\delta(1-1.15)\right]$$
$$= -13.14 \pm 3.5 \tag{5.16}$$

This low value agrees with Seattle experiment.

6. Conclusions

Measurement of y dependence of the asymmetry in electron-deuterium scattering is of crucial importance. If no strong y dependence is observed, the natural model discussed in Sect. 4 as well as the second model of Sec. 5 are eliminated. If atomic physics experiments persist in showing small or no parity violation while polarized electron deuterium experiments show no y dependence, the first model of Sect. 5 will have to be seriously considered. A test for this model is the asymmetry in electron-deuterium elastic scattering. It is possible to determine the four coupling constants involved in electron-hadron scattering by model-independent analysis as shown in Sect. 2. Even if all results should agree with W-S model at low q^2, it is still possible that at high q^2 the theory could deviate as discussed in model 1 of Sect. 4. The mass of Z boson provides a crucial test of W-S model.

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FIGURE CAPTIONS

Figure 1. The y dependence of the electron-deuterium asymmetry for the natural model (solid lines) compared with W-S model (dashed lines). The number on solid lines refer to different values of λ when $\beta = 0$ and $X = .25$.

Figure 2. Asymmetry in elastic electron-proton scattering as a function of Q^2 for natural model (solid lines) compared with W-S model (dashed lines).

Figure 3. Asymmetry in $e + p \to e + \Delta^+$ (1236) as a function of Q^2 for the natural model (solid lines) compared with W-S model (dashed lines).

Figure 4. Asymmetry in elastic electron-deuterium scattering as a function of Q^2 for the natural model (solid lines) compared with W-S model (dashed lines).

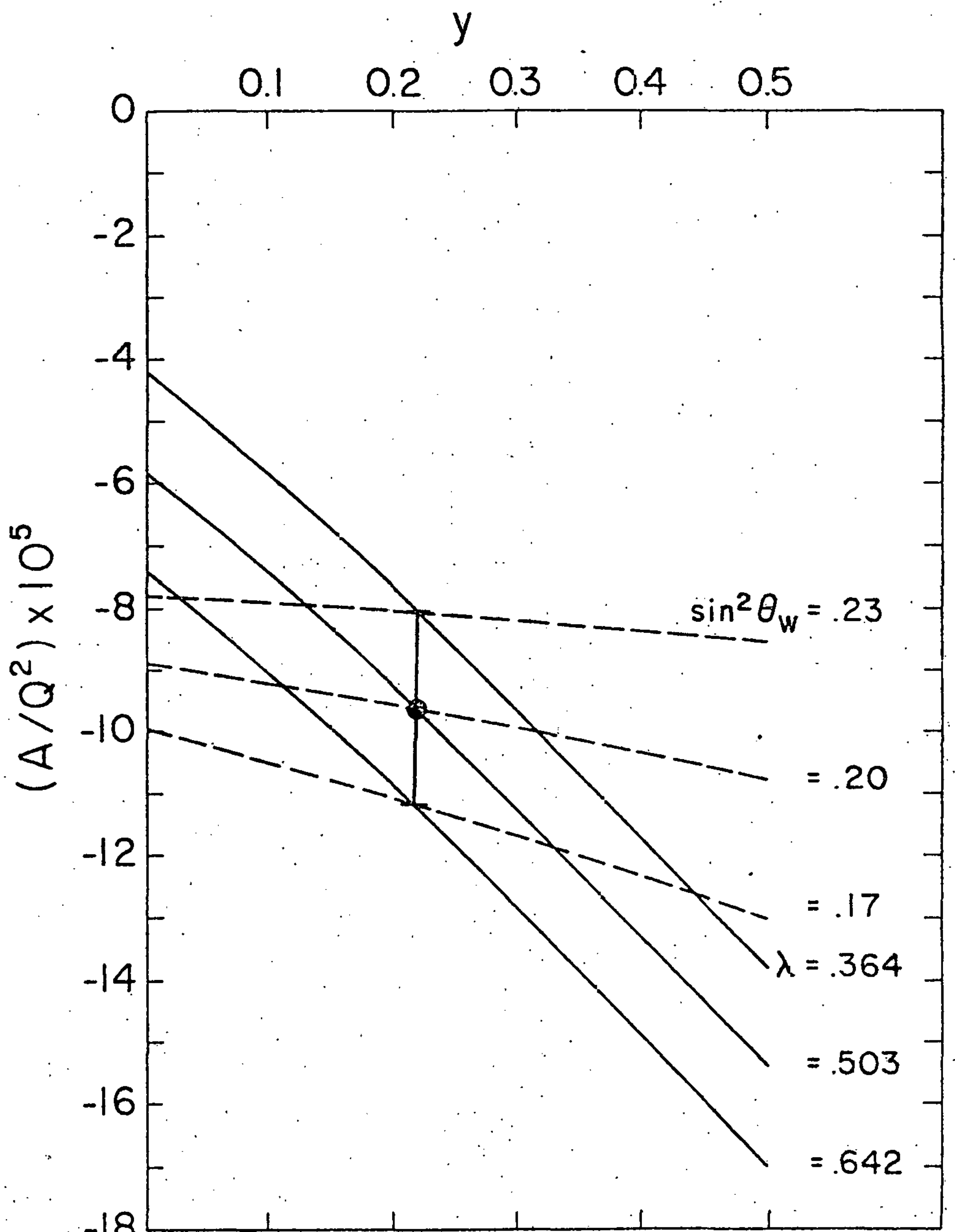
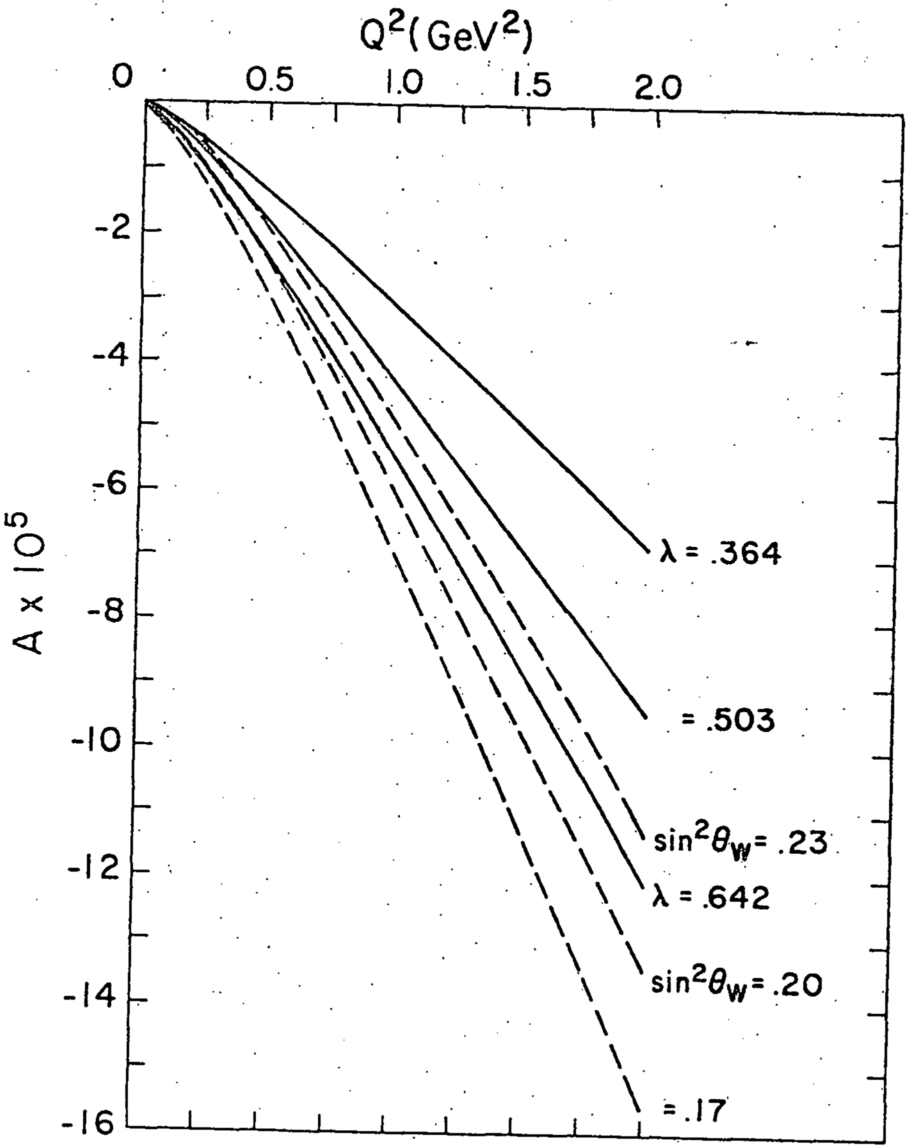
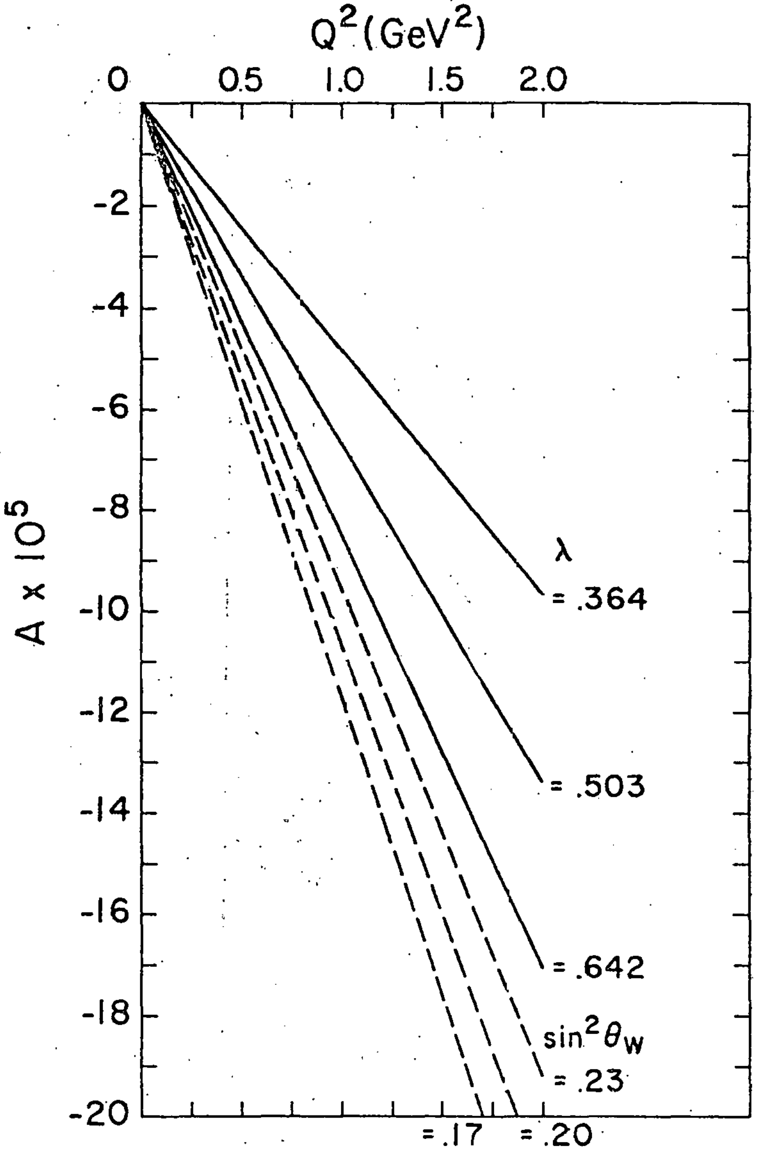


Fig. 1



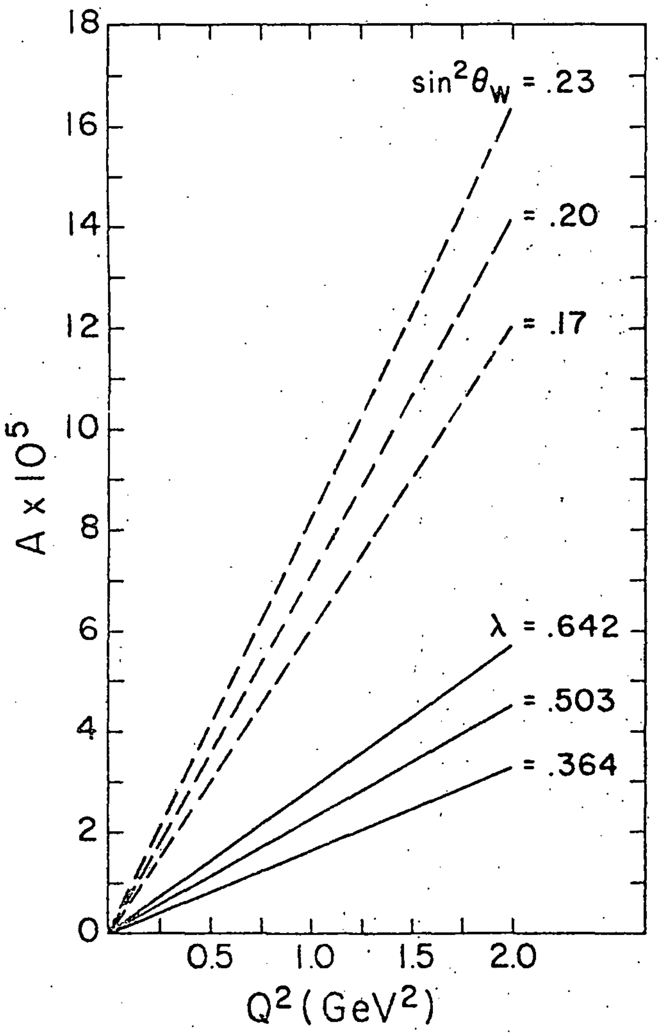
Q^2 (GeV^2)
0
0.5
1.0
1.5
2.0
A x 10^5
-2
-4
-6
-8
-10
-12
-14
-16
λ = .364
= .503
sin^2θ_W = .23
λ = .642
sin^2θ_W = .20
= .17

Fig. 2



Q^2 (GeV^2)
0
0.5
1.0
1.5
2.0
A x 10^5
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
λ
= .364
= .503
= .642
sin^2θ_W
= .23
= .17
= .20

Fig. 3



18
16
14
12
10
8
6
4
2
0
A x 10^5
sin²θ_W = .23
= .20
= .17
λ = .642
= .503
= .364
0.5
1.0
1.5
2.0
Q² (GeV²)

Fig. 4