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Implications for Gauge Theories if Search for Parity Nonconservation in Atomic Physics Fails

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Failure to detect parity-nonconserving effects in atomic transitions coupled with the available neutrino neutral-current data would appear to rule out all $SU(2)\otimes U(1)$ gauge theories which respect "natural" conservation laws for charm and strangeness and quark-lepton symmetry. We analyze a left-right symmetric "natural" (in the above sense) and quark-lepton symmetric $SU(2)_L\otimes SU(2)_R\otimes U(1)$ gauge theory and find that it accommodates all the features of neutral-current phenomena.

In a recent joint paper[1] by the University of Washington and University of Oxford collaboration, it has been reported that the parity-nonconserving optical rotation, R, in atomic bismuth is $R_{876\text{ nm}} = (-8\pm 3)\times 10^{-8}$ (Washington experiment), $R_{648\text{ nm}} = (+10\pm 8)\times 10^{-8}$ (Oxford experiment), where the quoted statistical error represents 2 standard deviations. Within the systematic uncertainty ($<\pm 10\times 10^{-8}$), each of these results is consistent[1] with $R=0$. The predictions of this effect in the Weinberg-Salam $SU(2)_L\otimes U(1)$ model[2] plus the atomic central-field approximation[3] is $R_{876\text{ nm}} = -3\times 10^{-7}$ and $R_{648\text{ nm}} = -4\times 10^{-7}$. The predictions for other $SU(2)\otimes U(1)$ models with *more* quarks, that (a) obey a "naturalness" condition[4] for charm and strangeness conservations to order G_F (called "natural" models henceforth) and that (b) have the number of leptons equal to the number of quark flavors, also predict similar numbers for R, after the parameters are adjusted to fit neutrino neutral-current experiments.[5-9] Thus, insofar as the approximations behind the theoretical estimates of the atomic parity-nonconserving effects are reliable,[10] the present neutral-current data imply the following:

(a) The original Weinberg-Salam $SU(2)\otimes U(1)$ model with Glashow-Iliopoulos-Maiani[11] mechanism is inconsistent.

(b) If there are four quarks and four leptons, $SU(2)\otimes U(1)$ is unacceptable as the weak gauge group.

(c) Furthermore, all $SU(2)\otimes U(1)$ gauge theories satisfying the restrictions of "naturalness" and quark-lepton symmetry (with arbitrary number of quarks) are also ruled out if quark charges are only $+\frac{2}{3}$ and $-\frac{1}{3}$.

(d) In fact, if the hints of parity nonconservation in $\nu_\mu e$ scattering[7-9] become confirmed, atomic physics experiments will rule out all "natural" $SU(2)\otimes U(1)$ theories (i.e., with or without quark-lepton symmetry. The reason for this is that in $SU(2)\otimes U(1)$ theories, there is only one massive neutral gauge boson (Z), which couples to the entire weak neutral current.[12] So, if νN and νe couplings involve V and A combinations for electron and hadron currents, eN coupling must then violate parity conservation. In this Letter, we point out that a previously suggested left-right-symmetric gauge model[13] based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$, with four quarks and four leptons is both "natural" and able to accommodate all the features of neutral-current phenomena. This model has other attractive features: (i) It has parity nonconservation arising purely as a result of spontaneous breakdown of the gauge symmetry, the same mechanism that gives boson and fermion masses in the theory,[13] and (ii) it provides a natural basis for CP-nonconserving interactions.

First, we present a model with four quark flavors.[13] For simplicity, we ignore CP nonconservation. The quarks and leptons are assigned to the following representations of the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$:

$$\begin{aligned}&(u_L, d_L(\theta_L)),\quad (c_L, s_L(\theta_L)),\quad (\tfrac{1}{2}, 0, \tfrac{1}{3});\\&(u_R, d_R(\theta_R)),\quad (c_R, s_R(\theta_R)),\quad (0, \tfrac{1}{2}, \tfrac{1}{3});\\&(\nu_L, e_L^-),\quad (\nu_L', \mu_L^-),\quad (\tfrac{1}{2}, 0, -1);\\&(\nu_R, e_R^-)\quad (\nu_R', \mu_R^-),\quad (0, \tfrac{1}{2}, -1).\end{aligned} \tag{1}$$

We impose a discrete left-right symmetry on the Lagrangian, which yields only two gauge couplings: $g_L = g_R = g$ for $SU(2)_L \otimes SU(2)_R$ and g' for U(1). These couplings can be written in terms of the electric charge, e, and an angle θ as $g = \sqrt{2}e \times \sec\theta$ and $g' = e\csc\theta$.

Before we can write down the neutral-current interaction, we will have to specify the Higgs sector and diagonalize the neutral gauge-boson mass matrix to find its eigenstates, which are the Z_1 and Z_2 bosons. As noted earlier,[13] to maintain left-right symmetry, in the Higgs sector, we must choose the following symmetric sets of Higgs bosons: $\chi_L(\frac{1}{2}, 0, 1)$ and $\chi_R(0, \frac{1}{2}, 1)$; $\delta_L(1, 0, 0)$ and $\delta_R(0, 1, 0)$ and $\varphi(\frac{1}{2}, \frac{1}{2}, 0)$. It has been shown earlier[13] that one can choose a Higgs potential such that one obtains the following sets of vacuum expectation values:

$$\langle \chi_L \rangle = \langle \chi_R \rangle = \begin{pmatrix} 0 \\ \lambda \end{pmatrix},$$

$$\langle \varphi \rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix} \text{ and } \langle \delta_L \rangle = 0 \text{ and } \langle \delta_R \rangle = \begin{pmatrix} 0 \\ b \\ 0 \end{pmatrix},$$

for a range of parameters in the potential. We can make $b \gg \lambda$, k, and k'. Since δ_R contributes to the mass of only the charged right-handed $W_R^\pm$ bosons, the above choice of b makes $M_{W_R} \gg M_{W_L}$, M_{Z_1}, M_{Z_2}. As a result, the right-handed charged-current interactions are suppressed, as required by experiment. Note that suppression of right-handed charged current is not necessarily a requirement if we have more than four quarks. Further, the photon and the neutral Z bosons can be written in terms of $W_{\mu 3}{}^L$ and $W_{\mu 3}{}^R$ and the U(1) gauge boson B_μ as

$$\begin{aligned}A_\mu &= (\cos\theta/\sqrt{2})(W_{3\mu}{}^L + W_{3\mu}{}^R) + \sin\theta B_\mu,\\ Z_{1\mu} &= (W_{3\mu}{}^L - W_{3\mu}{}^R)/\sqrt{2},\\ Z_{2\mu} &= \sin\theta(W_{3\mu}{}^L + W_{3\mu}{}^R)/\sqrt{2} - \cos\theta B_\mu.\end{aligned} \tag{2}$$

Their masses are

$$\begin{aligned}M_{Z_1}{}^2 &\simeq M_{W_L}{}^2(1+\epsilon),\\ M_{Z_2}{}^2 &\simeq M_{W_L}{}^2(1-\epsilon)\csc^2\theta,\end{aligned} \tag{3}$$

where

$$\epsilon = (k^2 + k'^2)/(\lambda^2 + k^2 + k'^2).$$

We can now write down the neutral-current interaction involving u and d quarks and leptons in terms of e and θ as follows:

$$\begin{aligned}L_{\rm neut} = {}&(ie/2\cos\theta)\{\bar{e}\gamma_\mu\gamma_5 e - \tfrac{1}{2}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu - \bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d\} Z_{1\mu}\\ &- (ie/\sin 2\theta)\{\cos 2\theta\,\bar{e}\gamma_\mu e + \tfrac{1}{2}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu - \tfrac{1}{3}(1 - 4\sin^2\theta)\bar{u}\gamma_\mu u - \tfrac{1}{3}(1 + 2\sin^2\theta)\bar{d}\gamma_\mu d\} Z_{2\mu}.\end{aligned} \tag{4}$$

It is clear from the above interaction that coupling of electrons to nucleons is parity conserving; *thus, one does not expect any parity-nonconserving effects in atoms to order* G_F. Furthermore, the neutrino interactions with both electrons and nucleons do not conserve parity.

The values of C_V and C_A for various other neutral current couplings in this model are given in Table I. For antineutrinos, only C_A changes sign. A fit with the $\bar{\nu}_e e$ scattering data of Reines, Gurr, and Sobel[8] yields for both $\epsilon \simeq 0$ and $\epsilon \simeq 0.1$ roughly $0.3 < x < 0.7$ (where $x = \cos^2\theta$). The present Gar-

TABLE I. Values of C_V and C_A for various neutral-current couplings of neutrinos are given for the four-quark model. C_V and C_A are defined by $H_\omega = (G_F/\sqrt{2})\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\bar{\psi}\gamma_\mu(C_V + C_A\gamma_5)\psi$; $x \equiv \cos^2\theta$.

Process	C_V	C_A
$\nu_e e^- \to \nu_e e^-$	$1 + \frac{1}{2}(2x-1)/(1-\epsilon)$	$1 - \frac{1}{2}(1+\epsilon)^{-1}$
$\nu_\mu e^- \to \nu_\mu e^-$	$(-\frac{1}{2} + x)/(1-\epsilon)$	$-[2(1+\epsilon)]^{-1}$
$\nu u \to \nu u$	$(-\frac{1}{2} + \frac{2}{3}x)/(1-\epsilon)$	$-[2(1+\epsilon)]^{-1}$
$\nu d \to \nu d$	$(\frac{1}{2} - \frac{1}{3}x)/(1-\epsilon)$	$[2(1+\epsilon)]^{-1}$

TABLE II. Predicted ratios $R^{\nu N}=\sigma^{\nu N}(\mathrm{NC})/\sigma^{\nu N}(\mathrm{CC})$, $R^{\bar{\nu}N}=\sigma^{\bar{\nu}N}(\mathrm{NC})/\sigma^{\nu N}(\mathrm{CC})$, and $R=\sigma^{\bar{\nu}N}(\mathrm{NC})/\sigma^{\nu N}(\mathrm{NC})$ are compared with experiment. Here NC and CC refer to neutral and charged currents, respectively.

Reaction	Predictions $\epsilon=0, x=0.4$	$\epsilon=0.1, x=0.3$	Experiment Ref. 7	Ref. 5	Ref. 6
$R^{\bar{\nu}N}$	0.39	0.37	0.39± 0.06	0.39± 0.10	0.39± 0.06
$R^{\nu N}$	0.33	0.36	0.25± 0.04	0.31± 0.06	0.24± 0.02
R	0.4	0.33	0.59± 0.14	≤0.61± 0.25	

gamelle data[7] for $\nu_\mu e$ scattering and the upper limit for $\bar{\nu}_\mu e$ scattering (90% confidence level) are also consistent with the above range of x and ϵ. For the ratio of inclusive neutral to charged-current neutrino scattering cross sections off isoscalar targets, our predictions are compared with experimental values in Table II. Our predictions for elastic νp and $\bar{\nu}p$ scattering[14] are listed in Table III for various values of the parameters. With the above choice of ϵ and x, we get $M_{Z_1}{}^2 = M_{W_L{}^+}{}^2 = 0.7 M_{Z_2}{}^2 = (87\ \mathrm{GeV})^2$. We further note that, in this model, neutrino masses are nonzero and arbitrary.

Models with more than four quarks and four leptons.—If we want to include right-handed currents[15] of type $(\bar{u}b)_R$, the new quark assignment of the model can be modified as follows: $(u_L, d_L(\theta))$, $(c_L, s_L(\theta))$ as left-handed doublets, and (u_R, b_R), (t_R, d_R) as right-handed doublets, with t_L, b_L, c_R and s_R, as singlets.[16] The interesting features of left-right symmetry are maintained in this way. We need not now have the δ_L- and δ_R-type Higgs mesons since we do not need to suppress any of the right-handed currents. We must then, of course, have six leptons and the new leptonic assignment is modified as follows: $(\nu_L, e_L{}^-)$, $(\nu_L, \mu_L{}^-)$ as left doublets, $(E_R{}^0, e_R{}^-)$, $(\nu_R{}^1, M_R{}^-)$ as right doublets, with $E_L{}^0$, $M_L{}^-$ and ν_R and $\mu_R{}^-$ as singlets. This again maintains the left-right symmetry. The important point to note is that, as long as $\tau_{3R}(u_R) = +\frac{1}{2}$, $\tau_{3R}(d_R) = -\frac{1}{2}$, and $\tau_{3R}(e_R{}^-) = -\frac{1}{2}$, the predictions for the neutral-current sector remain identical in any variant of the model. We, however, need a somewhat larger value of ϵ, to understand the high-y anomaly in antineutrino scattering.

Lastly, we would like to remark on the question of natural conservation laws for charm and strangeness in this class[4] of theories. The condition for naturalness is the same as in the SU(2) ⊗U(1) theory as long as we assign all right-handed fermions to the $\mathrm{SU}(2)_R$ group and left-handed ones to the $\mathrm{SU}(2)_L$ group. The condition is that, τ_{3L} and τ_{3R} for particles of charge $\frac{2}{3}$ must be $+\frac{1}{2}$, and for all particles of charge $-\frac{1}{3}$, it should be $-\frac{1}{2}$. From this point of view, the six-quark model just stated does not have natural conservation law for strangeness unless we put (c_R, s_R) and (t_L, b_L) in corresponding doublets. [By lepton-quark symmetry, $(M_{0R}, \mu_R{}^-)$ and $(E_{0L}, M_L{}^-)$ must also belong to the right and left doublets, respectively.] Thus, all the models we have discussed in this Letter have this elegant property.

To summarize, failure to observe parity non-

TABLE III. Predicted ratios for $R_{\mathrm{el}}{}^{\nu p} = \sigma(\nu p \to \nu p)/\sigma(\nu n \to \mu^- p)$, $R_{\mathrm{el}}{}^{\bar{\nu}p} = \sigma(\bar{\nu}p \to \bar{\nu}p)/\sigma(\bar{\nu}p \to \mu^+ n)$, $R = \sigma(\bar{\nu}p \to \bar{\nu}p)/\sigma(\nu p \to \nu p)$; m_A represents the mass that parametrizes the axial form factor of the proton.

Reaction	Predictions $\epsilon=0, x=0.4$ $m_A=0.85$ (GeV)	$m_A=1.15$ (GeV)	$\epsilon=0.1, x=0.3$ $m_A=0.85$ (GeV)	$m_A=1.15$ (GeV)	Experiments[a]
$R_{\mathrm{el}}{}^{\nu p}$	0.13	0.16	0.16	0.17	0.17± 0.05(HPW) 0.23± 0.09(CIR)
$p_{\mathrm{el}}{}^{\bar{\nu}p}$	0.11	0.19	0.13	0.17	0.20± 0.10(HPW)
R	0.30	0.37	0.3	0.3	0.4± 0.2(HPW)

[a]HPW (Harvard-Penn-Wisconsin): Cline *et al.*, Ref. 14. CIR (Columbia-Illinois-Rockefeller): Lee *et al.*, Ref. 14.

conservation in atomic transitions will rule out all "natural" quark-lepton symmetric $SU(2)_L \otimes U(1)$ gauge models. The $SU(2)_L \otimes SU(2)_R \otimes U(1)$ model with four quarks and four leptons appears to accommodate this and other neutral-current experiments and may provide interesting insight into CP and P nonconservation in weak interactions.[17] A six-quark extension of this model is possible, if we want to accommodate the y anomaly.

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[16]E. Ma, University of Oregon Institute of Theoretical Studies Report No. OTIS-68 (to be published), has discussed a similar model, but it suffers from the drawback that $m_u = m_d = 0$ to all orders in g and g', because of the absence of the Higgs multiplet φ in the model.

[17]We note that unlike the $SU(2)_L \otimes U(1)$ model with four quarks where the Yukawa interaction of the Higgs fields generates CP nonconservation [see S. Weinberg, Phys. Rev. Lett. 37, 657 (1976), and P. Sikivie, Phys. Lett. 65B, 141 (1976)], in the $SU(2)_L \otimes SU(2)_R \otimes U(1)$ models, all interactions (weak, electromagnetic as well as CP nonconservation ones) are generated by gauge principle.

Atomic-Number Dependence of Large-Transverse-Momentum Hadron Production by Protons*

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We have measured at Fermilab the production of hadrons at ~90° in the c.m. system as a function of incident proton energy, atomic number A of the production target, and the transverse momentum $p_\perp$ of the produced hadron. The A dependence of the production cross section of the hadrons can be described by a function $A^{\alpha(p_\perp)}$, where the power α rises with $p_\perp$. At $p_\perp \sim 5$ GeV/c, α is ~1.1 for $\pi^\pm$ and K^+, and ~1.3 for p, $\bar{p}$, and K^-. The energy dependence of the power is also measured.

In an earlier paper[1] we reported on the atomic-number (A) dependence of hadron production at large transverse momentum ($p_\perp$). Similar data have also been reported by other groups.[2,3] These results were surprising because the A dependence of the hadron yield, when fitted to a form $A^{\alpha(p_\perp)}$,