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PARITY VIOLATIONS IN ELECTRON-NUCLEON SCATTERING AND THE $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ ELECTROWEAK SYMMETRY *

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ABSTRACT

The $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ model of electroweak interactions is described with the most general gauge couplings g_L, g_R and g_{L+R}. The case in which neutrino neutral current interactions are identical to the standard $SU(2)_L \times U(1)_{L+R}$ model is discussed in detail. It is shown that with the weak angle lying in the experimental range $\sin^2\theta_w = 0.23 \pm 0.015$ and $1 < g_L^2/g_R^2 < 3$ it is possible to explain the amount of parity violation observed at SLAC and at the same time predict values of the "weak charge" in bismuth to lie in the range admitted by the controversal data from different experiments.

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The $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ model of electroweak interactions [1)] is usually discussed with the imposed discrete symmetry left ⟷ right that reduces the number of gauge couplings to just two. In general, the couplings $g_L(\equiv SU(2)_L)$, $g_R(\equiv SU(2)_R)$ and $g_{L+R}(\equiv U(1)_{L+R})$ can all be different in magnitude as is evident from conventional ideas on grand unified theories [2)]. For example, when SO(10) descends to $SU(3)_L \times U(1)_{em}$ through different intermediate sub-symmetries the gauge coupling $g_{10}(\equiv SO(10))$ splits into four distinct couplings g_L, g_R, g_{1C} $(\equiv U(1)_C)$ and $g_{3C}(\equiv SU(3)_C)$ at the renormalization point usually taken to be the mass of the weak gauge boson mediating left-handed charged weak interactions.

In this note the $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ model for electroweak interactions is described with the most general gauge couplings [3)] g_L, g_R and g_{L+R}. In order to keep in touch with unification ideas the $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ subgroup is extracted from the Pati-Salam group [4)] $SU(2)_L \times SU(2)_R \times SU(4)^C_{L+R}$ which can be naturally embedded in SO(10). This is briefly described.

The equivalent of $U(1)_{L+R}$ in $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ in $SU(4)^C_{L+R}$ is $U(1)^C_{L+R}$ ($\propto$ λ_{15} generator of SU(4)) and characterizes the (baryon-lepton) number of the theory). The gauge couplings of $U(1)^C_{L+R}$ and $U(1)_{L+R}$ are trivially related, $g_{L+R} = \sqrt{\frac{3}{2}}\ g_{1C}$. Spontaneous symmetry breaking of $SU(2)_L \times SU(2)_R \times SU(4)^C_{L+R}$ to $SU(3)^C_{L+R} \times U(1)_{em}$ is effected by Higgs scalars $A \sim (2,2,1)$, $B \sim (1,2,\bar{4})$, $C \sim (2,1,\bar{4})$, $D \sim (1,1,15)$, $E \sim (1,3,1)$ with vacuum expectation values $\langle A \rangle = \mathrm{diag}\ (a_1,a_2)$; $\langle B \rangle_{24} = b$; $\langle C \rangle_{24} = c$; $\langle D \rangle = \mathrm{diag}\ (d,d,d,-3d)$, $\langle E \rangle = (0,\epsilon,0)$. The resulting mass Lagrangian involving only the neutral fields (W^0_L, W^0_R, V^0_{15}) has the photon field A_μ and two massive neutrals $N_{1\mu}$, $N_{2\mu}$ as its physical eigenstates [3)] where

$$A/e = W^0_L/g_L + W^0_R/g_R - \left(\frac{2}{3}\right)^{1/2} V^0_{15}/g_{1C} , \qquad (1)$$

$$e^{-2} = g_L^{-2} + g_R^{-2} + (\tfrac{2}{3})\, g_{1C}^{-2} \quad , \tag{2}$$

$$N_1 = W_{(-)} \cos\beta + Y \sin\beta \quad , \quad , \tag{3}$$

$$N_2 = Y \cos\beta - W_{(-)} \sin\beta \tag{4}$$

with masses and the mixing angle defined as

$$M^3_{1(2)} = \tfrac{1}{2}\,(P_1 + P_2) + (-)\,\tfrac{1}{2}\,(P_1 - P_2)\,\sec 2\beta \quad , \tag{5}$$

$$\tan 2\beta = 2\Delta/(P_2 - P_1) \quad , \tag{6}$$

where e is the electric charge; $g^{-2} = g_L^{-2} + g_R^{-2}$; $W_{(-)}/g = W_L^0/g_R - W_R^0/g_L$; $Y/e = (\frac{2}{3})^{1/2}\, g(W_L^0/g_L + W_R^0/g_R)/g_{1C} + V_{15}^0/g$; $4P_1/g^2 = (g_L/g_R + g_R/g_L)^2\, a^2 + {} + g_L^2 c^2/g_R^2 + g_R^2 b^2/g_L^2$; $4P_2/g^2 = (3g_{1C}^2/2g^2 + 1)\,(b^2 + c^2)$; $a^2 = a_1^2 + a_2^2$; $4\Delta/g^2 = (3g_{1C}^2/2g^2 + 1)^{1/2}\,[g_R b^2/g_L - g_L c^2/g_R]$. The fermionic current coupling to Y^μ is vector, while that coupling to $W^\mu_{(-)}$, unlike in the $g_L = g_R$ case, is now an admixture of vector and axial vector parts. The weak angle $\sin^2\theta_w$ is defined in the usual way as

$$\sin^2\theta_w = e^2/g_L^2 = (3g_{1C}^2/2g_L^2)/(3\,{}_{1C}^{2}/2g^2 + 1) \ . \tag{7}$$

Mere substitution of $g_{L+R} = (\frac{3}{2})^{1/2}\, g_{1C}$ in all the above expressions involving g_{1C} gives relations that are correct for the more general $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ electroweak theory without recourse to any scheme of unification. The relevant Higgs scalars in this case are $A \sim (2,\bar{2},0)$, $B \sim (1,2,1)$, $C \sim (2,1,1)$, $E \sim (1,3,1)$ with vacuum expectation values $\langle A \rangle = \mathrm{diag}\,(a_1, a_2)$; $\langle B \rangle = (0,b)$; $\langle C \rangle = (0,c)$; $\langle E \rangle = (0,\epsilon,0)$.

Eqs.(3) and (4) give the effective "low energy" interaction Lagrangian for neutral current processes involving neutrinos and electrons as probes [5]. For muon neutrinos, the vector $(g_V^{(f)})$ and axial-vector (g_A^f) couplings of the fermion f ($f = u,d,e$) in units of $G_F/\sqrt{2}$ are:

$$g_V^u = \left\{\frac{1}{(1 + g_L^2/g_R^2)} - \frac{4}{3}\sin^2\theta_w\right\} G_V + \frac{(g_L^2 - g_R^2)}{2(g_L^2 + g_R^2)}\, G_A \quad ; \quad g_A^u = \tfrac{1}{2}\, G_A \ , \tag{8}$$

$$g_V^d = \left\{\frac{-1}{(1 + g_L^2/g_R^2)} + \frac{2}{3}\sin^2\theta_w\right\} G_V - \frac{(g_L^2 - g_R^2)}{2(g_L^2 + g_R^2)}\, G_A \quad ; \quad g_A^d = -\tfrac{1}{2}\, G_A \ , \tag{9}$$

$$g_V^e = \left\{\frac{-1}{(1 + g_L^2/g_R^2)} + 2\sin^2\theta_w\right\} G_V - \frac{(g_L^2 - g_R^2)}{2(g_L^2 + g_R^2)}\, G_A \quad ; \quad g_A^e = -\tfrac{1}{2}\, G_A \ . \tag{10}$$

For electron neutrinos scattering over electrons the couplings are modified due to charged current contribution

$$E_V^e = 1 + g_V^e \ ; \quad E_A^e = 1 + g_A^e \ . \tag{11}$$

The G_V and G_A in Eqs.(8)-(11) are defined as

$$G_V = (a^2+c^2)\,\{(1 + g_L^2/g_R^2)\, a^2 + b^2\}/\{a^2(b^2+c^2) + b^2c^2\} \quad , \tag{12}$$

$$G_A = (a^2+c^2)\, b^2/\{a^2(b^2+c^2) + b^2c^2\} \quad . \tag{13}$$

In electron-nucleon scattering the parity violating effects are described by the cross current terms $\frac{G_F}{\sqrt{2}}\, C_{VA}^q\, \bar{e}\gamma_\mu e\, \bar{q}\, \gamma^\mu\gamma_5 q$ and $\frac{G_F}{\sqrt{2}}\, C_{AV}^q\, \bar{e}\gamma_\mu\gamma_5 e\, \bar{q}\, \gamma^\mu q$ ($q = u,d$) where

$$C_{VA}^u = \{-H_1 + \{2(1 + g_L^2/g_R^2)\sin^2\theta_w - 1\}\, H_2\}\, G_A \quad , \tag{14}$$

$$C_{AV}^u = \{-H_1 + \{4/3\,(1 + g_L^2/g_R^2)\sin^2\theta_w - 1\}\, H_2\}\, G_A \ , \tag{15}$$

$$C_{VA}^d = \{H_1 - \{2(1 + g_L^2/g_R^2)\sin^2\theta_w - 1\}\, H_2\}\, G_A \quad , \tag{16}$$

$$C_{AV}^d = \{H_1 - \{2/3\,(1 + g_L^2/g_R^2)\sin^2\theta_w - 1\}\, H_2\}\, G_A \tag{17}$$

with $H_1 = \{(g_L^2 - g_R^2)/2\,(g_L^2 + g_R^2)\}\,(1 + b^2/c^2)$; $H_2 = (1 - g_L^2 c^2/g_R b^2)/(1 + g_L^2/g_R^2)$.

In deriving Eqs.(14) to (17) the momentum transfer q^2 as compared with the masses $m_{1(2)}$ has been neglected.

For neutrino neutral current interactions there are two cases of interest. (i) when $a^2 = 0$, G_V and G_A of Eqs.(9) and (10) are independent of b^2 and c^2. Both are equal to unity. In this case the couplings in Eqs.(8) to (11) simplify to those of the standard $SU(2)_L \times U(1)_{L+R}$ electroweak theory 6). These couplings do not carry any information about the masses of N_1 and N_2 and depend only on the weak angle $\sin^2\theta_w$. (ii) When $b^2 >> a^2, c^2$, once again G_V and G_A are equal to unity and the $SU(2)_L \times U(1)_{L+R}$ limit of the theory is achieved. In the second case the mass of N_2 is much heavier than the mass of N_1.

The fermions in the theory acquire their masses from the vacuum expectation values of the Higgs multiplet A. If $a^2 = 0$ then all the fermions are massless (or have vanishingly small masses for $a \simeq 0$). In Ref.5 the first case was referred to as the "chiral limit". Here the "chiral limit" case is considered in detail and the more general case in which $a^2 \neq 0$ is left for later. For $a^2 = 0$, since all neutrino interactions are identical to the standard $SU(2)_L \times U(1)_{L+R}$ theory, only the weak angle $\sin^2\theta_w$ that parametrizes the amplitudes of the various interactions in Eqs.(8) to (11) is an experimentally accessible quantity. Taking the present world averaged 7) value of $\sin^2\theta_w = 0.23 \pm 0.015$, Eq.(7) gives the following constraint on the gauge couplings:

$$(1 + g_L^2/g_R^2 + 2g_L^2/3g_{1C}^2)^{-1} = 0.23 \pm 0.015 \quad . \qquad (11)$$

For the case considered this is the maximum information that can be obtained from neutrino neutral current interactions. Further information on the gauge couplings comes from considering parity violating effects in electron nucleon scattering as is evident from the couplings from Eqs.(14) to (17). There are functions of $\sin^2\theta_w$, which is known from neutrino interactions, b^2/c^2 and g_L^2/g_R^2 that have now to be determined.

First, the predictions of the parity violating asymmetry for polarized electron-deuteron scattering 8) are discussed for various values of g_L^2/g_R^2, since this is the most accurately measured quantity at present. Then the values of the weak charge in bismuth are given as predictions in the light of controversy surrounding the various measurements 9).

In discussing these results the approximation $M_1^2, M_2^2 >> q^2$ (≡ momentum transfer) is implemented. Also, from Eq.(11) positivity of g_L^2/g_{1C}^2 requires g_L^2/g_R^2 to satisfy $0 < g_L^2/g_R^2 < 3.08$ for the upper limit of $\sin^2\theta_w = 0.245$ and $0 < g_L^2/g_R^2 < 3.63$ for the lower limit of $\sin^2\theta_w = 0.215$.

The asymmetry $A^{eD} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ for polarized electrons over deuterium is given by 10)

$$A^{eD} = \frac{9G_F}{10\sqrt{2}\,\pi\alpha} \left\{ \left(\frac{2}{3} C_{AV}^u - \frac{1}{3} C_{AV}^d\right) + \frac{1-(1-Y)^2}{1+(1-Y)^2} \left(\frac{2}{3} C_{VA}^u - \frac{1}{3} C_{VA}^d\right) \right\} , \qquad (12)$$

while the weak charge Q_w for heavy atoms with Z protons and (A-Z) neutrons is given by

$$Q_w = -2(A + Z)\, C_{AV}^u - 2\,(2A-Z)\, C_{AV}^d \quad . \qquad (13)$$

Table I gives predictions of A^{eD}, Q_w, M_1 and M_2 for various values of $\sin^2Q_w$ and g_L^2/g_R^2 in the range discussed in the text. These values are to be compared with predictions of the $SU(2)_L \times U(1)_{L+R}$ theory which are:

$\sin^2Q_w$	0.19	0.2	0.215	0.23	0.245
$A^{eD}/q^2\ 10^{-5}$	-10.2	-9.6	-8.9	-8.2	-73
Q_w	-105.6	-108	-113	-118	-123
$M_Z (= M_1, M_2 \to \infty)$	96	93.7	91	89	87

From the above numbers predictions of A^{eD} lie in the allowed experimental range 8) $A^{eD}|_{exp} = -9.5 \pm 1.6 \times 10^{-5}\, q^2$ (Y = 0.21) for values of $\sin^2\theta_w \lesssim 0.23$. On the other hand, from Table I, predictions of $A^{eD}/q^2\ 10^{-5}$ in the

$SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ model can cover values of $\sin^2\theta_w > 0.23$ with $g_L^2/g_R^2 > 1$.[11)] Another point to observe is that for a fixed value of $\sin^2\theta_w$ and g_L^2/g_R^2, $|A^{eD}|$ increases while $|Q_w|$ decreases with increasing b^2/c^2 (M_1 and M_2 increase with increasing b^2/c^2). At present the controversy surrounding the experimental measurements are such that they admit Q_w from order -40 to order -125. Therefore by varying g_L^2/g_R^2 in the range 1 to 3 and masses (M_1, M_2) for a fixed $\sin^2\theta_w$ it is possible to accommodate the results of these experiments. For example, with $\sin^2\theta_w = 0.23$, A^{eD}/q^2 10^{-5} is -9.5 for the sets ($Q_w = -41$, $M_1 = 81$ GeV, $M_2 = 152$ GeV, $g_L^2/g_R^2 = 2$), ($Q_w = -83$, $M_1 = 85$ MeV, $M_2 = 262$ GeV, $g_L^2/g_R^2 = 2.5$), ($Q_w = -91$, $M_1 = 85$ GeV, $M_2 = 450$ GeV, $g_L^2/g_R^2 = 3.0$). In the light of the above discussion more accurate measurements of Q_w are called for. If Q_w is found to fall short of the predicted $SU(2)_L \times U(1)_{L+R}$ value at fixed $\sin^2\theta_w$, this will be "low energy" evidence in favour of the $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ structure with the modification of $g_L \neq g_R$ as the symmetry underlying the electroweak interactions. Measuring the asymmetry A^{eD} at various values of Y will also help. Other equally important tests of the theory are measurements of parity violating asymmetries in electron-proton scattering and determining the couplings $C_{AV}^{u,d}$, $C_{VA}^{u,d}$ (Eqs.(14)-(17)) directly from electron-hydrogen scattering.

Finally, conventional ideas on the evolution of coupling constants in grand unified theories can lead to $g_L^2 > g_R^2$ at some renormalization point at low energies usually taken to be the mass of the charged weak boson W_L. For example, g_L and g_R are equal when SO(10) descends to $SU(2)_L \times SU(2)_R \times SU(4)_{L+R}^C$. To achieve $g_L^2/g_R^2 > 1$, the $SU(2)_R$ must break earlier than $SU(2)_L$. Much earlier breaking of $SU(2)_R$ over $SU(2)_L$ can lead to the desired value $g_L^2 \sim$ (2 to 3) g_R^2. In this case $\langle E\rangle \sim (1,3,1)$ will be several orders of magnitude greater than $\langle B\rangle \sim (1,2,\bar{4})$. These ideas, the more general case of $a^2 \neq 0$, and variation of A^{eD} with Y will be covered in a later publication.

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11) Fit to A^{eD} exist for $g_L^2/g_R^2 < 1$. But values of $\sin^2\theta_W$ lower than 0.20 are required.

Table I

Predictions of masses M_1, M_2 (in GeV), parity violating effects A^{eD} (in units of $q^2\ 10^{-5}$, $y = 0.21$) and Q_W in electron-nucleon scattering in $SU(2)_L \times SU(2)_R \times U(1)_{L+R}$ theory.

$\sin^2\theta_W$	0.215				0.230				0.245			
g_L^2/g_R^2	1.5	2	2.5	3	1.5	2	2.5	3	1.5	2	2.5	3
M_1	89	80.8	84	85	81.8	81	80	82	68	76	77.5	80
M_2	177	135	185	276	132	152	189	339	110	147	215	656
A^{eD}	-8.0	-9.9	-11.0	-11.2	-7.0	-9.5	-11.2	-11.1	-6.2	-9.9	-11.1	-10.9
Q_W	-76.8	-21.5	-51	-68	-40.6	-41	-41	-65	-12	-21.5	-42	-67
M_1	89.5	85	86	86	86.2	85	83	83.3	81.4	80	80	81.3
M_2	205	157	205	287	177	194	223	366	146	171	240	734
A^{eD}	-8.2	-9.5	-10.5	-11.0	-7.5	-8.9	-10.2	-10.6	-6.9	-9.0	-10.1	-10.0
Q_W	-87	-52	-65	-71.5	-80	-76	-67	-74	-58	-56	-63	-80
M_1	90	89	88	87.5	87.5	86	85	84.7	84	84.5	83	82
M_2	238	230	250	336	223	221	262	416	179	255	306	804
A^{eD}	-8.4	-9.2	-9.9	-10.4	-78	-8.7	-9.5	-10.0	-7.0	-8.0	-9.0	-9.5
Q_W	-94	-88	-83	-84	-95	-87	-83	-85	-83	-97	-89	-88
M_1	90.3	89.6	89	88	88	87	86	85	86	85	84	83
M_2	268	266	288	353	268	273	312	450	270	285	352	868
A^{eD}	-8.5	-9.1	-9.6	-10.3	-7.9	-8.5	-9.1	-9.7	-7.2	-7.9	-8.5	-9.2
Q_W	-98.5	-95	-91	-87	-103	-99	-95	-91	-107	-103	-98	-94

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