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Difficulty of $V(e)V(q)+A(e)A(q)$ neutral currents in $SU(2)\times U(1)\times U(1)$ theory

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It is shown that the condition of no Adler-Bell-Jackiw anomalies in the $SU(2)\times U(1)\times U(1)'$ gauge theory having vector-type C_μ coupling and the right-handed fermions all in the singlet representations excludes the possibility that the neutral-current interaction of the leptons and hadrons is of the form $VV+AA$.

The original Weinberg-Salam (WS) model[1] of gauge theories has successfully predicted the existence of neutrino related hadronic neutral currents as confirmed by CERN, Fermilab, and Brookhaven experiments.[2] However, the need for extending the gauge groups and fermion representations was often motivated by new experimental discoveries.[3]

The proliferation of quarks and leptons began with the so-called "high-y anomaly". A right-handed quark doublet was introduced. Since the high-y anomaly has not been confirmed by more recent experiment,[4] this motivation for the introduction of the right-handed doublets in $SU(2)\times U(1)$ theory is no longer operative. Hence the WS theory seems to describe all neutrino-hadron experiments.[5] However, a problem still remains: Is there parity violation in atomic physics? The first-generation experiments on this have brought conflicting results. The Washington (Seattle) group[6] did not see the effect, but the Novosibirsk group[7] saw the effect agreeing with the WS predictions. The first[8] of the second-generation experiments again by the Washington group confirmed their earlier result. Therefore, it is fair to say that the parity-violation problem in atomic physics is not settled yet.

Nevertheless, we may *ask if it is possible to have no parity violation in atomic physics when the right-handed fermions are all assigned in the singlet representations*. Of course it is not possible in $SU(2)\times U(1)$ theory. But is it still the case if there exist more neutral gauge bosons? We would like to answer this with the previously considered $SU(2)\times U(1)\times U(1)'$ model.[9] [The method may easily be extended to any number of U(1) factors. In principle, some of these U(1) factors can be remnants of, e.g., the superunified gauge group or any simple flavor group whose rank is larger than 2.]

In this theory, we have two massive neutral vector bosons. Hence one may think[10] that it is always possible to have the $VV+AA$ form of neutral currents, and the parity is conserved by the electron-related neutral currents but apparently violated by the neutrino-related neutral-current experiments because of the left-handed (right-handed) laboratory $\nu(\bar{\nu})$. Our results show that it is not the case. The main reason is the constraint coming from no triangle anomalies which is often overlooked in phenomenological application[9] of gauge models. In an $SU(2)\times U(1)\times U(1)'$ gauge theory, the charge can be defined by the formula $Q=T_3+(Y+C)/2$ where Y and C are two different weak hypercharges. But we can always redefine the gauge fields such that only one of the hypercharges appear in the charge relation

$$Q=T_3+\tfrac{1}{2}Y. \qquad (1)$$

We will use this convention, because it gives simpler expressions for the triangle anomaly. There are gauge fields A_μ^i $(i=1,2,3)$, B_μ, and C_μ. Fermions are grouped into "$V-A$" doublets and "$V+A$" singlets as in the WS model,

$$L_e=\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L,\ \nu_{eR}, e_R;\ \text{etc.}$$
$$L_d=\begin{pmatrix}u'\\ d\end{pmatrix}_L,\ u_R, d_R;\ \text{etc.} \qquad (2)$$

We choose to work with the minimal scalar multiplets, one doublet and another singlet,

$$\phi=\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix},\quad \phi'=(\phi_0'). \qquad (3)$$

We proceed to construct neutral-current interactions of the form $V(e)V(q)+A(e)A(q)$ while maintaining the renormalizability of the theory, in particular *requiring the absence of triangle anomalies*.[11] Since this constraint is independent of the detailed mass matrix of the gauge bosons, we choose any independent set of gauge fields, say

$$A_\mu^i (i=1,2,3),\ A_\mu (\equiv \text{photon}),\ C_\mu \qquad (4)$$

and require at the outset that there be no triangle anomalies. In general, the photon field A_μ is a linear combination of primordial fields A_μ^3, B_μ, and C_μ. The gauge fields in (4) are associated with the matrices,

$$T_i (i=1,2,3), Q, C. \qquad (5)$$

Note that the use of relation (1) leaves the gauge boson C_μ couplings completely arbitrary. Were $Q=T_3+(Y+C)/2$ used, Y or C would be arbitrary though $(Y+C)$ is not. The merit of using (1) here lies in that the triangle graphs involving A_μ^i and A_μ (≡ photon) do not cause anomaly in the case of equal number of "$V-A$" leptons ($Q=0,-1$) and color-tripled quark doublets ($Q=\frac{2}{3},-\frac{1}{3}$). This is because[12]

$$\text{Tr} Q T^2 = 0, \qquad (6)$$

or equivalently $\text{Tr}\, Q=0$ is satisfied in this case. Extending the argument of vanishing d_{abc} terms to include C_μ, we find the following constraints:

$$\text{Tr} C T^2 = 0, \qquad (7)$$

$$\text{Tr} Q C^2 = 0, \qquad (8)$$

$$\text{Tr} C Q^2 = 0, \qquad (9)$$

$$\text{Tr} T_3 Q C = 0, \qquad (10)$$

$$\text{Tr} C^3 = 0. \qquad (11)$$

The "$V-A$" fermions contribute to (6)–(11) positively whereas the "V+A" fermions contribute negatively. Further, (8), (9), and (11) get contributions from the singlets.

To be more general a right-handed neutrino is introduced, thus making it massive in principle. Treating the three lepton families (ν_e, e), (ν_μ, μ), and (ν_τ, τ) and the three quark families (u,d), (c,s), and (t,b) symmetrically, we have eight c parameters, c_ν^L, c_e^L, c_u^L, c_d^L, c_ν^R, c_e^R, c_u^R, and c_d^R. Five of these can be removed from the relations (7)–(11), thus leaving three unknown c's. However, if the C_μ coupling is vector, i.e., $c_\nu^L=c_\nu^R$, $c_e^L=c_e^R$, etc., then only (7) and (10) give nontrivial results for four remaining c parameters, leaving only two unknown c's. We will study this simple case of vector C_μ coupling in the following. As far as fermions are concerned one of these parameters can be absorbed into the redefinition of the gauge coupling g''. We then find for the vector-type C_μ couplings that

$$\begin{aligned} c_\nu &= \alpha, \\ c_e &= -1+2\alpha, \\ c_u &= \tfrac{2}{3}-\alpha, \\ c_d &= -\tfrac{1}{3}. \end{aligned} \qquad (12)$$

TABLE I. Eigenvalues of Y and C.

	Y	C
L_e	-1	$(\alpha, -1+2\alpha)$
ν_R	0	α
e_R	-2	$-1+2\alpha$
L_d	$\frac{1}{3}$	$(\frac{2}{3}-\alpha, -\frac{1}{3})$
u_R	$\frac{4}{3}$	$\frac{2}{3}-\alpha$
d_R	$-\frac{2}{3}$	$-\frac{1}{3}$
ϕ	1	(c_+, c_0)
ϕ'	0	c'

If the neutrino appears only as a member of the left-handed doublet and yet the C_μ coupling is of vector type, we must have $\alpha=0$. In this case the eigenvalues of C are simply given by the respective electric charges. For completeness we give the eigenvalues of Y and C in Table I. Hence the gauge-invariant Lagrangian is

$$\begin{aligned} \mathcal{L} = &-\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \tfrac{1}{4}(\partial_\mu C_\nu - \partial_\nu C_\mu)^2 \\ &- \bar{L}_e \gamma_\mu \left[\partial_\mu - ig\tfrac{1}{2}\vec{\tau}\cdot\vec{A}_\mu + \tfrac{1}{2} ig' B_\mu - \tfrac{1}{2} ig'' \begin{pmatrix} \alpha & 0 \\ 0 & -1+2\alpha \end{pmatrix} C_\mu \right] L_e \\ &- \bar{e}_R \gamma_\mu (\partial_\mu + ig' B_\mu + \tfrac{1}{2} ig''(1-2\alpha) C_\mu) e_R - \bar{\nu}_{eR}\gamma_\mu (\partial_\mu - \tfrac{1}{2} ig''\alpha C_\mu)\nu_{eR} \\ &+ (\mu\text{-family terms}) + (\tau\text{-family terms}) - \bar{L}_d \gamma_\mu \left[\partial_\mu - \tfrac{1}{2} ig\vec{\tau}\cdot\vec{A}_\mu - \tfrac{1}{6} ig' B_\mu - \tfrac{1}{2} ig'' \begin{pmatrix} \frac{2}{3}-\alpha & 0 \\ 0 & \frac{1}{3} \end{pmatrix} C_\mu \right] L_d \\ &- \bar{u}_R \gamma_\mu [\partial_\mu - \tfrac{1}{3} i2g' B_\mu - \tfrac{1}{2} ig''(\tfrac{2}{3}-\alpha) C_\mu] u_R - \bar{d}_R \gamma_\mu (\partial_\mu + \tfrac{1}{3} ig' B_\mu + \tfrac{1}{6} ig'' C_\mu) d_R \\ &+ (s\text{-family terms}) + (b\text{-family terms}) + (\text{Yukawa-coupling terms}) \\ &- \left| \partial_\mu \phi - \tfrac{1}{2} ig\vec{\tau}\cdot\vec{A}_\mu - \tfrac{1}{2} ig' B_\mu \phi - \tfrac{1}{2} ig'' \begin{pmatrix} c_+ & 0 \\ 0 & c_0 \end{pmatrix} C_\mu \phi \right|^2 - |\partial_\mu \phi' - \tfrac{1}{2} ig'' c' C_\mu \phi'|^2 - V(\phi, \phi'), \end{aligned} \qquad (13)$$

where the Yukawa-coupling terms generate fermion masses as usual through spontaneous symmetry breaking and V is the usual Higgs potential having minima at $\langle\phi^0\rangle = v/\sqrt{2}$ and $\langle\phi'\rangle = v'/\sqrt{2}$. While the charged vector bosons $W_\mu^{\pm} = (A_\mu{}^1 \mp iA_\mu{}^2)/\sqrt{2}$ have the mass

$$M_W = \tfrac{1}{2}gv\,, \tag{14}$$

those of the physical neutral gauge bosons A_μ, Z_μ, and X_μ are governed by

$$\tfrac{1}{2}(M_Z{}^2 Z_\mu{}^2 + M_X{}^2 X_\mu{}^2) + 0 \times A_\mu{}^2$$

$$= \tfrac{1}{8}v^2(gA_\mu{}^3 - g'B_\mu - g''c_0C_\mu)^2 + \tfrac{1}{8}v'^2(g''c'C_\mu)^2\,. \tag{15}$$

The fields of the mass eigenstates are related to the primordial fields through

$$\begin{pmatrix} A_\mu{}^3 \\ B_\mu \\ C_\mu \end{pmatrix} = M \begin{pmatrix} A_\mu \\ Z_\mu \\ X_\mu \end{pmatrix}, \tag{16}$$

where M is

$$\begin{bmatrix} \sin\theta, & -\cos\theta\cos\psi, & -\cos\theta\sin\psi \\ \cos\theta\sin\zeta, & \sin\theta\cos\psi\sin\zeta + \sin\psi\cos\zeta, & \sin\theta\sin\psi\sin\zeta - \cos\psi\cos\zeta \\ -\cos\theta\cos\zeta, & -\sin\theta\cos\psi\cos\zeta + \sin\psi\sin\zeta, & -\sin\theta\sin\psi\cos\zeta - \cos\psi\sin\zeta \end{bmatrix}. \tag{17}$$

The neutral gauge bosons couple to fermions as

$$\begin{aligned}\mathcal{L}^{NC} = {} & (\bar\nu_e, \bar e)_L i\gamma_\mu \begin{pmatrix} \tfrac{1}{2}gA_\mu{}^3 - \tfrac{1}{2}g'B_\mu + \tfrac{1}{2}\alpha g''C_\mu, & 0 \\ 0, & -\tfrac{1}{2}gA_\mu{}^3 - \tfrac{1}{2}g'B_\mu + \tfrac{1}{2}g''(-1+2\alpha)C_\mu \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \\ & + \bar e_R i\gamma_\mu[-g'B_\mu - \tfrac{1}{2}g''(1-2\alpha)C_\mu]e_R + \bar\nu_R i\gamma_\mu(\tfrac{1}{2}g''\alpha C_\mu)\nu_R \\ & + (\bar u, \bar d)_L i\gamma_\mu \begin{pmatrix} \tfrac{1}{2}gA_\mu{}^3 + \tfrac{1}{6}g'B_\mu + \tfrac{1}{2}g''(\tfrac{2}{3}-\alpha)C_\mu, & 0 \\ 0, & -\tfrac{1}{2}gA_\mu{}^3 + \tfrac{1}{6}g'B_\mu - \tfrac{1}{6}g''C_\mu \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_L \\ & + \bar u_R i\gamma_\mu[\tfrac{2}{3}g'B_\mu + g''(\tfrac{1}{3} - \tfrac{1}{2}\alpha)C_\mu]u_R + \bar d_R i\gamma_\mu(-\tfrac{1}{3}g'B_\mu - \tfrac{1}{6}g''C_\mu)d_R\,.\end{aligned} \tag{18}$$

There are relations between θ, ψ, ζ and g, g', g'', c_0, v, and $c'v'$. The electromagnetic coupling is correctly given if

$$g\sin\theta = g'\cos\theta\sin\zeta\,, \tag{19}$$

along with either

(i) $\cos\zeta = 0$,

or

(ii) $\alpha = 0$.

Then the case (i) gives

$$e = g\sin\theta = \frac{gg'}{(g^2+g'^2)^{1/2}}\,, \tag{20}$$

while the case (ii) gives

$$e = g\sin\theta - \tfrac{1}{2}g''\cos\theta\cos\zeta\,. \tag{21}$$

We have given in Tables II and III the respective neutral-current couplings of cases (i) and (ii) explicitly. The entries of the Tables are the coupling strength of the neutral gauge bosons, Z_μ and X_μ, to the respective fermion currents. For case (i) $\sin\zeta$ is set to $+1$.

We now proceed to examine the possibility of having the neutral-current interactions of the $V(e)V(q) + A(e)A(q)$ form. Consider, for example, the case where J_μ^Z is a vector current and J_μ^X is an axial-vector current. Then we must have from case (i) that $\cos\psi = 0$, which results in $1 - 4\sin^2\theta = 0$, $1 - \frac{8}{3}\sin^2\theta = 0$, and $1 - \frac{4}{3}\sin^2\theta = 0$ all at the same time. This is clearly impossible. The case (ii) gives $\cos\psi + \sin\theta\sin\psi\cot\zeta = 0$, which results $\cos\theta\sin\psi - 3\tan\theta(\sin\theta\sin\psi - \cos\psi\cot\zeta) = 0$, $\cos\theta\sin\psi - \frac{5}{3}\tan\theta(\sin\theta\sin\psi - \cos\psi\cot\zeta) = 0$, and $\cos\theta\sin\psi + \frac{1}{3}\tan\theta(\sin\theta\sin\psi - \cos\psi\cot\zeta) = 0$ again all at the same time. These relations are mutually inconsistent. Similar inconsistency arises when the role of J_μ^Z and J_μ^X are interchanged.

Thus we have shown that the constraint of no triangle anomaly excludes the $VV + AA$ form of the neutral-current interactions in the $SU(2) \times U(1) \times U(1)'$ theory in which the right-handed fermions are all singlets and the C_μ coupling is a vector type. We must face the parity violations in atomic physics in such models. If we relax the assumption on the vector-type C_μ coupling, the analysis

TABLE II. Neutral-current couplings of case (i).

Currents	Z_μ	X_μ
$i\bar{\nu}\gamma_\mu \nu$	$-\frac{1}{4}g\sec\theta\cos\psi+\frac{1}{2}\alpha g''\sin\psi$	$-\frac{1}{4}g\sec\theta\sin\psi-\frac{1}{2}\alpha g''\cos\psi$
$i\bar{\nu}\gamma_\mu\gamma_5\nu$	$-\frac{1}{4}g\sec\theta\cos\psi$	$-\frac{1}{4}g\sec\theta\sin\psi$
$i\bar{e}\gamma_\mu e$	$\frac{1}{4}g\sec\theta\cos\psi-\frac{1}{2}g''(1-2\alpha)\sin\psi$	$\frac{1}{4}g\sec\theta\sin\psi(1-4\sin^2\theta)$ $+\frac{1}{2}g''(1-2\alpha)\cos\psi$
$i\bar{e}\gamma_\mu\gamma_5 e$	$\frac{1}{4}g\sec\theta\cos\psi$	$\frac{1}{4}g\sec\theta\sin\psi$
$i\bar{u}\gamma_\mu u$	$-\frac{1}{4}g\sec\theta\cos\psi(1-\frac{8}{3}\sin^2\theta)$ $+\frac{1}{2}g''(\frac{2}{3}-\alpha)\sin\psi$	$-\frac{1}{4}g\sec\theta\sin\psi(1-\frac{8}{3}\sin^2\theta)$ $-\frac{1}{2}g''(\frac{2}{3}-\alpha)\cos\psi$
$i\bar{u}\gamma_\mu\gamma_5 u$	$-\frac{1}{4}g\sec\theta\cos\psi$	$-\frac{1}{4}g\sec\theta\sin\psi$
$i\bar{d}\gamma_\mu d$	$\frac{1}{4}g\sec\theta\cos\psi(1-\frac{4}{3}\sin^2\theta)$ $-\frac{1}{6}g''\sin\psi$	$\frac{1}{4}g\sec\theta\sin\psi(1-\frac{4}{3}\sin^2\theta)$ $+\frac{1}{6}g''\cos\psi$
$i\bar{d}\gamma_\mu\gamma_5 d$	$\frac{1}{4}g\sec\theta\cos\psi$	$\frac{1}{4}g\sec\theta\sin\psi$

would require far more complexity, thus losing the simplicity of the theory.

The conclusion reached in this paper does not apply to the case in which right-handed doublets are utilized. For example, if one starts out with a larger vectorlike group[13] which contains SU(2) $\times$ U(1) $\times$ U(1)$'$, there would necessarily be right-handed nonsinglet fermions and there would be no triangle anomalies.

Note added in proof. After we submitted this paper for publication, the result of the polarized electron scattering by deuteron[14] was reported, which essentially rules out the neutral-current interaction of the form $V(e)V(q)+A(e)A(q)$.

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TABLE III. Neutral-current couplings of case (ii).

Currents	Z_μ	X_μ
$i\bar{\nu}\gamma_\mu \nu$	$-\frac{1}{4}g\sec\theta\cos\psi-\frac{1}{4}g\tan\theta\cot\zeta\sin\psi$	$-\frac{1}{4}g\sec\theta\sin\psi+\frac{1}{4}g\tan\theta\cot\zeta\cos\psi$
$i\bar{\nu}\gamma_\mu\gamma_5\nu$	$-\frac{1}{4}g\sec\theta\cos\psi-\frac{1}{4}g\tan\theta\cot\zeta\sin\psi$	$-\frac{1}{4}g\sec\theta\sin\psi+\frac{1}{4}g\tan\theta\cot\zeta\cos\psi$
$i\bar{e}\gamma_\mu e$	$\frac{1}{4}g\cos\theta\cos\psi-\frac{3}{4}g\tan\theta(\sin\theta\cos\psi+\sin\psi\cot\zeta)$ $-\frac{1}{2}g''(-\sin\theta\cos\psi\cos\zeta+\sin\psi\sin\zeta)$	$\frac{1}{4}g\cos\theta\sin\psi-\frac{3}{4}g\tan\theta(\sin\theta\sin\psi-\cos\psi\cot\zeta)$ $+\frac{1}{2}g''(\sin\theta\sin\psi\cos\zeta+\cos\psi\sin\zeta)$
$i\bar{e}\gamma_\mu\gamma_5 e$	$\frac{1}{4}g\sec\theta\cos\psi+\frac{1}{4}g\tan\theta\sin\psi\cot\zeta$	$\frac{1}{4}g\sec\theta\sin\psi+\frac{1}{4}g\tan\theta\cos\psi\cot\zeta$
$i\bar{u}\gamma_\mu u$	$-\frac{1}{4}g\cos\theta\cos\psi+\frac{5}{12}g\tan\theta(\sin\theta\cos\psi+\sin\psi\cot\zeta)$ $+\frac{1}{3}g''(-\sin\theta\cos\psi\cos\zeta+\sin\psi\sin\zeta)$	$-\frac{1}{4}g\cos\theta\sin\psi+\frac{5}{12}g\tan\theta(\sin\theta\sin\psi-\cos\psi\cot\zeta)$ $-\frac{1}{3}g''(\sin\theta\sin\psi\cos\zeta+\cos\psi\sin\zeta)$
$i\bar{u}\gamma_\mu\gamma_5 u$	$-\frac{1}{4}g\sec\theta\cos\psi-\frac{1}{4}g\tan\theta\sin\psi\cot\zeta$	$-\frac{1}{4}g\sec\theta\sin\psi+\frac{1}{4}g\tan\theta\cos\psi\cot\zeta$
$i\bar{d}\gamma_\mu d$	$\frac{1}{4}g\cos\theta\cos\psi-\frac{1}{12}g\tan\theta(\sin\theta\cos\psi+\sin\psi\cot\zeta)$ $+\frac{1}{6}g''(\sin\theta\cos\psi\cos\zeta-\sin\psi\sin\zeta)$	$\frac{1}{4}g\cos\theta\sin\psi-\frac{1}{12}g\tan\theta(\sin\theta\sin\psi-\cos\psi\cot\zeta)$ $+\frac{1}{6}g''(\sin\theta\sin\psi\cos\zeta+\cos\psi\sin\zeta)$
$i\bar{d}\gamma_\mu\gamma_5 d$	$\frac{1}{4}g\sec\theta\cos\psi+\frac{1}{4}g\tan\theta\sin\psi\cot\zeta$	$\frac{1}{4}g\sec\theta\sin\psi-\frac{1}{4}g\tan\theta\cos\psi\cot\zeta$

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