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Consequences of a simple phenomenological $V-A$ model for neutral currents*

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We examine the experimental implications of a simple phenomenological $V-A$ model of neutral currents, in which the neutral current belongs to the same generalized isospin triplet as the charged currents with zero Cabibbo angle, and in which the current-current effective Lagrangian describing neutral-current interactions has a different over-all strength from that describing charged-current couplings.

There have been many recent experiments[1-6] establishing the existence of neutral currents in neutrino-induced reactions. The key question for the future now becomes that of determining the precise form of the neutral-current couplings. Ultimately, one would wish for a direct experimental determination of the coefficients appearing in a general neutral-current effective Lagrangian, but this is unlikely to be possible with the limited data expected to be available in the near future. What does seem practical in the short term is deciding between several alternative simple one- or two-parameter candidate structures for the phenomenological neutral-current coupling. The most prominent such candidate is of course the effective Lagrangian predicted by the Weinberg-Salam[7] $SU(2)\otimes U(1)$ gauge model, and indeed it has become conventional to interpret experimental results in terms of constraints on the single parameter $\sin^2\theta_W$ appearing in the Weinberg-Salam model formulas.[8] Alternative neutral-current couplings involving pure vector[9] (or pure axial-vector[10]) hadronic neutral currents have also been discussed in the literature, and give predictions with characteristic differences from those of the Weinberg-Salam model. The purpose of this note is to discuss yet a third simple candidate model for neutral-current couplings, involving pure $V-A$ hadronic and leptonic neutral currents, with an eye to examining the experimental tests which distinguish it from the Weinberg-Salam and pure V (A) alternatives. The model[11] which we analyze is specified by the following three properties:

(I) The neutral currents are of strict $V-A$ form.

(II) In a hypothetical world with zero Cabibbo angle θ_C, the charge-changing currents $J|_{\theta_C=0}$, $J^\dagger|_{\theta_C=0}$ and the neutral current J_N are the members of a generalized isospin triplet. [In the actual world with $\theta_C\neq 0$, this exact SU(2) is broken by the Cabibbo rotation in the charged currents, which in our model has no analog in the neutral current.]

(III) The current-current effective Lagrangian describing neutral-current interactions has a different over-all strength from that describing charged-current interactions, introducing one parameter to be fitted to experiment.

In accordance with (I) and (II), we take the neutral current J_N^λ to have the $V-A$ form[12]

$$\begin{aligned}
J_N^\lambda &= J_{Nl}^\lambda + J_{Nh}^\lambda ,\\
J_{Nl}^\lambda &= \tfrac{1}{2}\bar\nu_\mu\gamma^\lambda(1-\gamma_5)\nu_\mu - \tfrac{1}{2}\bar\mu\gamma^\lambda(1-\gamma_5)\mu\\
&\quad + \tfrac{1}{2}\bar\nu_e\gamma^\lambda(1-\gamma_5)\nu_e - \tfrac{1}{2}\bar e\gamma^\lambda(1-\gamma_5)e ,\\
J_{Nh}^\lambda &= V_3^\lambda - A_3^\lambda .
\end{aligned} \tag{1a}$$

Together with the $\theta_C=0$ limit of the charged currents $J|_{\theta_C=0}$, $J^\dagger|_{\theta_C=0}$

$$\begin{aligned}
J^\lambda|_{\theta_C=0} &= J_l^\lambda + J_h^\lambda|_{\theta_C=0} ,\\
J_l^\lambda &= \bar\nu_\mu\gamma^\lambda(1-\gamma_5)\mu + \bar\nu_e\gamma^\lambda(1-\gamma_5)e ,\\
J_h^\lambda|_{\theta_C=0} &= V_{1+i2}^\lambda - A_{1+i2}^\lambda ,
\end{aligned} \tag{1b}$$

the neutral-current forms a generalized isospin triplet when $\nu_e e$ and $\nu_\mu\mu$ are treated as leptonic isospin doublets, thus maintaining lepton-hadron universality. In accordance with (III), the effective Lagrangians for neutral and charge-changing currents are taken to be (with G the Fermi constant)

$$\begin{aligned}
\mathcal{L}_{N(\mathrm{eff})} &= \epsilon(G/\sqrt{2})J_{N\lambda}J^{N\lambda} ,\\
\mathcal{L}_{(\mathrm{eff})} &= (G/\sqrt{2})J_\lambda^\dagger J^\lambda .
\end{aligned} \tag{2}$$

The parameter ϵ, which characterizes the relative strengths of the neutral- and charged-current interactions, will be determined from experiment (see below). Writing out all relevant terms in both effective Lagrangians we have (for $\theta_C=0$)

$$\mathcal{L}_{(\text{eff})}+\mathcal{L}_{N(\text{eff})}=(G/\sqrt{2})[\bar{\nu}_e\gamma^\lambda(1-\gamma_5)e\,\bar{e}\gamma_\lambda(1-\gamma_5)\nu_e+\bar{\nu}_\mu\gamma^\lambda(1-\gamma_5)\mu\,\bar{\mu}\gamma_\lambda(1-\gamma_5)\nu_\mu$$
$$+(V^\lambda_{1+i2}-A^\lambda_{1+i2})\bar{\mu}\gamma_\lambda(1-\gamma_5)\nu_\mu+(V^\lambda_{1+i2}-A^\lambda_{1+i2})\bar{e}\gamma_\lambda(1-\gamma_5)\nu_e+\text{adjoint}]$$
$$+(\epsilon G/\sqrt{2})[-\tfrac{1}{2}\bar{\nu}_\mu\gamma^\lambda(1-\gamma_5)\nu_\mu\bar{e}\gamma_\lambda(1-\gamma_5)e-\tfrac{1}{2}\bar{\nu}_e\gamma^\lambda(1-\gamma_5)\nu_e\bar{e}\gamma_\lambda(1-\gamma_5)e$$
$$+(V^\lambda_3-A^\lambda_3)\bar{\nu}_\mu\gamma^\lambda(1-\gamma_5)\nu_\mu+(V^\lambda_3-A^\lambda_3)\bar{\nu}_e\gamma^\lambda(1-\gamma_5)\nu_e]\,. \quad (3)$$

The semileptonic neutral-current piece is

$$(\epsilon G/\sqrt{2})(V^\lambda_3-A^\lambda_3)\bar{\nu}_l\gamma_\lambda(1-\gamma_5)\nu_l,\quad l=\mu, e \quad (4)$$

to be compared with the Weinberg-Salam model form

$$(G/\sqrt{2})(V^\lambda_3-A^\lambda_3-2\sin^2\theta_W J^\lambda_{\text{em}}+\text{isoscalar})\times\bar{\nu}_l\gamma_\lambda(1-\gamma_5)\nu_l,\quad l=\mu, e\,. \quad (5)$$

Hence a particularly simple recipe for obtaining results in our case from semileptonic calculations in the Weinberg-Salam model is as follows: (A) Set[13] $\sin^2\theta_W=0$ and neglect possible isoscalar strangeness and "charm" current contributions. (B) Scale $G\to\epsilon G$, i.e., multiply *rates* by ϵ^2. For the leptonic sector, the Fierz transformation for a $V-A$ interaction leads to

$$\bar{\nu}_l\gamma^\lambda(1-\gamma_5)\nu_l\,\bar{l}\gamma_\lambda(1-\gamma_5)l=\bar{\nu}_l\gamma^\lambda(1-\gamma_5)l\,\bar{l}\gamma_\lambda(1-\gamma_5)\nu_l,\quad l=\mu, e\,. \quad (7)$$

Thus for $\bar{\nu}_l l$ scattering we have the effective Lagrangian

$$(G/\sqrt{2})(1-\tfrac{1}{2}\epsilon)\bar{\nu}_l\gamma^\lambda(1-\gamma_5)l\,\bar{l}\gamma_\lambda(1-\gamma_5)\nu_l,\quad l=\mu, e \quad (8a)$$

while for $\bar{\nu}_\mu e$ scattering, we have just the piece

$$(G/\sqrt{2})(-\tfrac{1}{2}\epsilon)\bar{\nu}_\mu\gamma^\lambda(1-\gamma_5)\nu_\mu\bar{e}\gamma_\lambda(1-\gamma_5)e\,. \quad (8b)$$

In Table I we give the (g_V, g_A) values for the complete set of neutrino- and antineutrino-induced leptonic reactions for the $V-A$ model Lagrangian [Eq. (3)] together with those of the Weinberg-Salam model. (The predictions of the "standard" $V-A$ theory, with no neutral currents, are obtained from Table I by setting $\epsilon=0$.)

We detail below comparisons of the $V-A$ model with experiment and with predictions of the Weinberg-Salam model [and also, where appropriate, with predictions of the pure V (A) model].

(i) Deep-inelastic neutrino scattering. Let us define the standard ratios of deep-inelastic cross sections

$$R_\nu\equiv\frac{\sigma(\nu_\mu T\to\nu_\mu X)}{\sigma(\nu_\mu T\to\mu^- X)},\quad R_{\bar{\nu}}\equiv\frac{\sigma(\bar{\nu}_\mu T\to\bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu T\to\mu^+ X)}, \quad (9)$$

with T an isotopically neutral target. Because the $V-A$ neutral and charged hadronic currents are in the same $I=1$ multiplet, we find

$$R_{\bar{\nu}}/R_\nu=1\,,\qquad \tfrac{1}{2}(R_\nu+R_{\bar{\nu}})=\tfrac{1}{2}\epsilon^2\,. \quad (10)$$

By contrast, in the pure V (A) model one has $R_{\bar{\nu}}/R_\nu\approx 3$, while in the Weinberg-Salam model this ratio is a function of $\sin^2\theta_W$ and lies roughly in the range $R_{\bar{\nu}}/R_\nu\sim 1.5-2.0$ for $\sin^2\theta_W\sim 0.3-0.4$. Experimental results to date are

CERN Gargamelle[2]: $R_\nu=0.22\pm0.03$, $R_{\bar{\nu}}=0.43\pm0.12$; (11a)

FNAL Experiment 1A[3,4]: $R_\nu=0.12\pm0.04$, $R_{\bar{\nu}}=0.32\pm0.08$; (11b)

Caltech-FNAL "raw" data[6]: $R_\nu=0.22$, $R_{\bar{\nu}}=0.33$. (11c)

Averaging the numbers of Eqs. (11a) and (11b) and treating errors as purely statistical, we find

$$R_{\bar{\nu}}/R_\nu=2.1\pm0.53\,, \quad (12a)$$

or as a 90% confidence limit

$$1.2<R_{\bar{\nu}}/R_\nu<3.0\,. \quad (12b)$$

Although the Weinberg-Salam model is favored by the data, neither the pure V (A) nor the $V-A$ model is strongly excluded. Again averaging the numbers

TABLE I. The (g_V, g_A) values for the $V-A$ model discussed in the text and for the Weinberg-Salam model. The differential cross section is obtained from g_V and g_A via the formula[22] (E_ν, E_e denote respectively the laboratory initial neutrino and final electron energies)

$$\frac{d\sigma}{dE_e}=\frac{G^2 m_e}{2\pi}\left[(g_V+g_A)^2+(g_V-g_A)^2\left(1-\frac{E_e}{E_\nu}\right)^2+\frac{m_e E_e}{E_\nu^2}(g_A{}^2-g_V{}^2)\right].$$

Reaction	Weinberg-Salam model g_V	Weinberg-Salam model g_A	$V-A$ model g_V	$V-A$ model g_A
$\nu_e e^-\to e^-\nu_e$	$\frac{1}{2}+2\sin^2\theta_W$	$\frac{1}{2}$	$1-\frac{1}{2}\epsilon$	$1-\frac{1}{2}\epsilon$
$\bar{\nu}_e e^-\to e^-\bar{\nu}_e$	$\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$	$1-\frac{1}{2}\epsilon$	$-(1-\frac{1}{2}\epsilon)$
$\nu_\mu e^-\to e^-\nu_\mu$	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$	$-\frac{1}{2}\epsilon$	$-\frac{1}{2}\epsilon$
$\bar{\nu}_\mu e^-\to e^-\bar{\nu}_\mu$	$-\frac{1}{2}+2\sin^2\theta_W$	$\frac{1}{2}$	$-\frac{1}{2}\epsilon$	$\frac{1}{2}\epsilon$

of Eqs. (11a) and (11b), we find

$$\tfrac{1}{2}(R_\nu + R_{\bar\nu}) = 0.20 \pm 0.02\,, \tag{13}$$

which when substituted into Eq. (10) gives for the $V-A$ model parameter ϵ the value

$$\epsilon^2 \approx 0.40\,, \quad \epsilon \approx \pm 0.63\,. \tag{14}$$

(ii) Weak π^0 production and the measurement of $R'({}_{13}\mathrm{Al}^{27})$. This can be obtained from the calculation of Adler *et al.*,[14] modified by the prescription of Eq. (6). We expect therefore $R'({}_{13}\mathrm{Al}^{27}) = 0.422$ (from Ref. 14 with $\sin^2\theta_W = 0$) $\times 0.4$ (from ϵ^2) $= 0.17$. Hence the $V-A$ prediction here is similar to that of the Weinberg-Salam model, which predicts R' in the range $\sim 0.22-0.18$ for $\sin^2\theta_W \sim 0.3-0.4$. An early neutrino experiment of W. Lee[15] gave a 90% confidence level upper limit $R' < 0.14$; more recent experiments[6,16] show positive evidence for neutral-current-induced pion production.

(iii) $\nu p \to \nu p$ scattering. Weinberg[17] has estimated that in the Weinberg-Salam model

$$\left.\frac{d\sigma(\nu p \to \nu p)/dq^2}{d\sigma(\nu n \to \mu^- p)/dq^2}\right|_{W-S} = 0.25 \tag{15}$$

at $\sin^2\theta_W = 0$, so our recipe of Eq. (6) predicts $0.25 \times 0.4 = 0.10$ for this ratio. By way of comparison, for the favored range of Weinberg angles $\sin^2\theta_W \sim 0.3-0.4$, the Weinberg-Salam model prediction[17] for this ratio is $\sim 0.16-0.19$. The experimental value given by an early neutrino experiment of Cundy *et al.*[18] is 0.12 ± 0.06. An interesting feature of the $(V-A)_3$ model is that $\sigma(\nu p \to \nu p) = \sigma(\nu n \to \nu n)$. (They are not equal in the Weinberg-Salam model, except at $\sin^2\theta_W = 0$, because J_{em} has an isoscalar part.) Hence for an isoscalar target nucleus, where the rates for $n \to p$ and $p \to n$ charge exchange are equal, the $V-A$ model prediction remains 0.10 independent of charge-exchange corrections, as long as nucleon absorption in the target nucleus can be neglected.

(iv) $\bar\nu_e e^- \to e^- \bar\nu_e$, $\nu_\mu e^- \to e^- \nu_\mu$. For the process $\bar\nu_e e^- \to e^- \bar\nu_e$ Table I yields $g_V = -g_A = 0.68$ for $\epsilon = +0.63$ and $g_V = -g_A = 1.32$ for $\epsilon = -0.63$, giving the predictions

$$\sigma(\bar\nu_e e^- \to e^- \bar\nu_e) = 0.25 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV}), \quad \epsilon = +0.63$$

$$\sigma(\bar\nu_e e^- \to e^- \bar\nu_e) = 0.94 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV})\,, \quad \epsilon = -0.63 \tag{16}$$

both of which are compatible with the 90% confidence level upper limit

$$\sigma(\bar\nu_e e^- \to e^- \bar\nu_e) < 1.3 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV}) \tag{17}$$

set by Gurr *et al.*[19,20] For the processes $\nu_\mu e^- \to e^- \nu_\mu$ and $\bar\nu_\mu e^- \to e^- \bar\nu_\mu$ Table I yields respectively $g_V = g_A = 0.32$ and $g_V = -g_A = -0.32$ for $\epsilon = +0.63$. (Reversing the sign of ϵ changes the signs of both g_V and g_A and thus leaves cross sections invariant.) Hence the $V-A$ model cross-section predictions for $\bar\nu_\mu$, ν_μ-e scattering are

$$\sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu) = 0.054 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV})\,, \tag{18a}$$

$$\sigma(\nu_\mu e^- \to e^- \nu_\mu) = 3\sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu) = 0.16 \times 10^{-41}\ \mathrm{cm}^2 (E_\nu/\mathrm{GeV})\,. \tag{18b}$$

By way of comparison, the corresponding predictions of the Weinberg-Salam model, for $\sin^2\theta_W = 0.35$, are

$$\sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu)_{W-S} = 0.21 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV})\,,$$

$$\sigma(\nu_\mu e^- \to e^- \nu_\mu)_{W-S} = 0.10 \times 10^{-41}\ \mathrm{cm}^2 (E_\nu/\mathrm{GeV})\,. \tag{19}$$

Current 90% confidence level experimental limits on these cross sections, as obtained by the CERN Gargamelle group,[1,20] are

$$0.03 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV}) < \sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu) < 0.3 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV})\,, \tag{20a}$$

$$\sigma(\nu_\mu e^- \to e^- \nu_\mu) < 0.26 \times 10^{-41}\ \mathrm{cm}^2 (E_\nu/\mathrm{GeV})\,. \tag{20b}$$

In obtaining Eqs. (20) from the experimental data, which have an electron energy cutoff $E_e > 300$ MeV, an isotropic center-of-mass scattering cross section ($d\sigma/d\cos\theta^* \propto d\sigma/dE_e = \text{constant}$) is assumed.[20] This assumption is valid for $\nu_\mu e^- \to e^- \nu_\mu$ in the $V-A$ model, so Eq. (18b) can be compared directly with Eq. (20b). However, the differential cross section $d\sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu)$ in the $V-A$ model is proportional to $(1 - E_e/E_{\bar\nu})^2$, and so to compare Eq. (18a) with Eq. (20a) we must multiply the former by a factor $\sim (1 - 300/1500)^2 \approx 0.64$ (taking a typical antineutrino energy as ~ 1.5 GeV), giving the effective $V-A$ model prediction

$$\sigma(\bar\nu_\mu e^- \to e^- \bar\nu_\mu)_{\mathrm{eff}} = 0.035 \times 10^{-41}\ \mathrm{cm}^2 (E_{\bar\nu}/\mathrm{GeV})\,. \tag{18a$'$}$$

The $V-A$ predictions of Eqs. (18a$'$) and (18b), as well as the Weinberg-Salam model predictions of Eq. (19), are compatible with the experimental limits of Eq. (20).

In conclusion, we list here some further properties of the $V-A$ model discussed above:

(v) The same isotopic rotation argument leading to Eq. (10) shows that neutrino-induced neutral and charged deep-inelastic processes have the same x and y distributions. The same statement holds for antineutrino-induced reactions. (Of

course, the distributions for neutrino- and antineutrino-induced processes are different.)

(vi) Since the neutral weak current is pure isovector, low-energy pion production by the neutral current should be $\Delta(1238)$ dominated.

(vii) Similarly, since the neutral current has no isoscalar component, the diffractive production of ω, ϕ from $\nu+p(n)\to\nu+(\omega,\phi)+p(n)$ is forbidden.

(viii) On nuclear targets we expect neutral-current-induced Gamow-Teller transitions and giant dipole resonance excitation, but with altered strengths from those predicted in the Weinberg-Salam model.

(ix) Coherent nuclear scattering effects[21] will be proportional to $\langle I_3\rangle \propto N-Z$ (the neutron excess) rather than to $A=N+Z$. Hence the effect will vanish in isoscalar nuclei like He^4 or C^{12}.

(x) Finally, at the price of introducing a second parameter (and losing lepton-hadron universality) the relative strengths of the purely leptonic and semileptonic effective Lagrangians can be altered. This modification will not change the semileptonic predictions *(i)*–*(iii)*, *(v)*–*(ix)* enumerated above.

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