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Addendum to "Prospects for a second neutral vector boson at low mass in SO(10)"

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An SO(10) model proposed previously is modified so as to allow for a legitimate fermion mass spectrum consistent with a low-mass Z_2. This drastically changes the neutral-current phenomenology of the original theory. The modified model reproduces more of the low-energy phenomenology of the standard model. All axial-vector-type neutral-current couplings at $q^2=0$ are identical to those in the standard model. The coupling of Z_2 to $u\bar{u}$ is enhanced, making it easier to detect the Z_2 in pp and $\bar{p}p$ colliders.

It is well known that SO(10) has rank 5, one higher than SU(5). It therefore contains an extra neutral gauge boson (Z_2). Several authors[1] have discussed a class of models in which the Z_2 mass is allowed to be relatively low (~ 250 GeV), while the mass of the lighter neutral vector boson (Z_1), which is necessarily lighter than the standard-model[2] Z_0 according to a theorem of Georgi and Weinberg,[3] is within 2% of the Z_0 mass. In this class of models, the electroweak gauge group is minimally extended to $SU(2)_L \times U(1)_a \times U(1)_b$. For the case $SO(10) \to SU(5) \times U(1)_X$, $a=Y$ (the weak hypercharge) and $b=X$. For the case $SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R$, $a=B-L$ and $b=R$, where $U(1)_{B-L}$ comes from $SU(4) \to SU(3)_c \times U(1)_{B-L}$ and $U(1)_R$ from $SU(2)_R \to U(1)_R$.

In the SO(10) example studied by Robinett and Rosner (RR),[1] the electroweak group is spontaneously broken by vacuum expectation values of scalar fields belonging to the spinor representation ($\underline{16}$) of SO(10). Within the context of $SU(2) \times U(1) \times U(1)$, the phenomenology of this model was considered earlier by Deshpande and Iskandar.[1] The neutrino neutral-current couplings at $q^2=0$ with this choice of Higgs representation turn out to be identical to those in the standard model.

There is an intrinsic problem of this model in SO(10): It cannot generate fermion masses. Since each fermion generation is assigned to a $\underline{16}$ of SO(10), scalar fields that can generate fermion masses via the conventional Yukawa interactions must belong to

$$\underline{16} \times \underline{16} = \underline{10} + \underline{126} + \underline{120} \quad . \tag{1}$$

None of these is present in a model with only Higgs 16-plets. An attempt was made to generate fermion masses from second-order contributions of the 16-plet scalar fields.[4] This turns out to be inconsistent with a low-mass Z_2: the smallness of the neutrino mass requires the mass of Z_2 to be large ($\gtrsim 10^7$ GeV).[5] Recently, a legitimate fermion-mass model consistent with a low-mass Z_2 has been constructed.[6] It requires the addition of SO(10) singlet fermion fields and 10-plet complex scalar fields to the model with only 16-plets of scalars and fermions. The singlet fermions will not affect the gauge interactions of the theory. The additional 10-plet scalar fields, however, can alter the neutral-current interactions, in fact, quite dramatically. It is the purpose of the present note to comment on these changes. Their phenomenological implications were first analyzed in $SU(2)_L \times I_{3R} \times U(1)_{B-L}$ by Deshpande and Iskandar (third work in Ref. 1), and we show that present data still allow quite low values of M_{Z_2}. The production of Z_2 in pp and $\bar{p}p$ collisions also turns out to be easier than in the the model considered by RR.

Listed in Table I are the scalar fields used in the present model to break the $SU(2)_L \times U(1)_a \times U(1)_b$ symmetry, together with their relevant quantum numbers. ϕ_1 is an $SU(2)_L$ singlet contained in the $\underline{16}$, while ϕ_2^u and ϕ_2^d are the two $SU(2)_L$ doublets contained in a $\underline{10}$. They are all assumed to have real vacuum expectation values (VEV's). Actually, for three fermion generations, three sets of 10-plet scalar fields are required in the fermion-mass model of Ref. 6. Since their contributions to the gauge-boson masses simply add, we consider for simplicity only one $\underline{10}$.

In what follows only the case $SU(2)_L \times U(1)_Y \times U(1)_X$ will be considered. The neutral-boson mass matrix has the

TABLE I. Assumed scalar fields leading to $SU(2)_L \times U(1)_a \times U(1)_b \to U(1)_{EM}$.

Scalar field	VEV	$2I_{3L}$	$Y=2(Q-I_{3L})$	$2\sqrt{10}X$	$2I_{3R}$	$B-L$
ϕ_1	$V_1/\sqrt{2}$	0	0	-5	-1	$+1$
ϕ_2^u	$V_2^u/\sqrt{2}$	-1	$+1$	$+2$	$+1$	0
ϕ_2^d	$V_2^d/\sqrt{2}$	$+1$	-1	-2	-1	0

form

$$\mu^2 = M_0^2 \begin{array}{ccc} I_{3L} & \frac{Y}{2} & X \end{array} \left| \begin{array}{ccc} \cos^2\theta & -\sin\theta\cos\theta & -\frac{2\hat{g}}{\sqrt{10}}\cos\theta \\ -\sin\theta\cos\theta & \sin^2\theta & \frac{2\hat{g}}{\sqrt{10}}\sin\theta \\ -\frac{2\hat{g}}{\sqrt{10}}\cos\theta & \frac{2\hat{g}}{\sqrt{10}}\sin\theta & \hat{g}^2(\frac{2}{5}+\frac{5}{2}r) \end{array} \right| . \quad (2)$$

Here

$$r \equiv \left[\frac{V_1}{V_2}\right]^2 , \quad (3)$$

where

$$V_2^2 \equiv (V_2^u)^2 + (V_2^d)^2 . \quad (4)$$

All other parameters are as defined in RR.[1] In particular, M_0 is the mass of the standard Z_0. For large r, the masses of Z_1 and Z_2 behave as

$$M_1/M_0 \approx 1 - 2/25r , \quad (5)$$

$$M_2/M_0 \approx (\tfrac{5}{2}\hat{g}^2 r + \text{const})^{1/2} . \quad (6)$$

Equation (5) should be compared with Eq. (3.19) in RR. It is obvious that the present model is closer to the standard model than is the model considered by RR in the sense that M_1 is closer to M_0 for the same value of r.

Following Georgi and Weinberg,[3] the effective neutral-current interaction Hamiltonian for the present model is found to be

$$\mathscr{H}_N = \mathscr{H}_N^0 + \Delta\mathscr{H}_N , \quad (7)$$

where

$$\mathscr{H}_N^0 = \frac{2}{V_2^2}[\bar{\psi}\gamma^\mu(I_{3L} - \sin^2\theta\, Q)\psi][\bar{\psi}\gamma_\mu(I_{3L} - \sin^2\theta Q)\psi] \quad (8)$$

is the effective Hamiltonian in the standard model and

$$\Delta\mathscr{H}_N = \frac{2}{V_1^2}\left\{\frac{4}{25}[\bar{\psi}\gamma^\mu(I_{3L} - \sin^2\theta\, Q)\psi][\bar{\psi}\gamma_\mu(I_{3L} - \sin^2\theta\, Q)\psi] + \frac{8}{5\sqrt{10}}[\bar{\psi}\gamma^\mu(I_{3L} - \sin^2\theta\, Q)\psi][\bar{\psi}\gamma_\mu X\psi] + \tfrac{2}{5}[\bar{\psi}\gamma^\mu X\psi][\bar{\psi}\gamma_\mu X\psi]\right\} . \quad (9)$$

Using the identity which relates various SO(10) generators,

$$(\tfrac{2}{5})^{1/2}X - \tfrac{3}{5}(I_{3L} - \sin^2\theta\, Q) = I_{3R} - \tfrac{3}{5}\cos^2\theta\, Q , \quad (10)$$

$\Delta\mathscr{H}_N$ can be recast in the form

$$\Delta\mathscr{H}_N = \frac{2}{V_1^2}\{\bar{\psi}\gamma^\mu[I_{3L} + I_{3R} - \tfrac{1}{5}(3+2\sin^2\theta)Q]\psi\} \times \{\bar{\psi}\gamma_\mu[I_{3L} + I_{3R} - \tfrac{1}{5}(3+2\sin^2\theta)Q]\psi\} . \quad (11)$$

Note that $\Delta\mathscr{H}_N$ is purely vectorlike. Consequently, *all axial-vector-type neutral-current couplings are identical to those in the standard model,* and the present model will turn out to reproduce more of the standard-model neutral-current phenomenology than the model with only Higgs 16-plets.

The phenomenology of the Hamiltonian (8)+(11) has been examined previously in an $SU(2)_L \times I_{3R} \times U(1)_{B-L}$ model, as mentioned.[7] Our analysis will reach qualitatively similar conclusions, but we incorporate information on $\sin^2\theta$ in a slightly different way. The model-independent analysis of Deshpande and Johnson[1] turns out to reach conclusions almost identical to those in the present, more specific, approach. Others[8,9] have also studied electroweak theories in which $\Delta\mathscr{H}_N$ is purely vectorlike.

The form of $\Delta\mathscr{H}_N$ in Eq. (11) changes the low-energy neutral-current interactions in RR.[1] The neutrino interactions are no longer the same as in the standard model. Instead, constraints on the parameter r are derived from data on neutrino experiments. The most significant constraints apply to parameters measured in deep-inelastic scattering on hadrons. These may be expressed as[7,10]

$$\epsilon_L(u) = \tfrac{1}{2} - \tfrac{2}{3}x + \frac{1}{r}[\tfrac{1}{2} - \tfrac{2}{15}(3+2x)] = 0.340 \pm 0.033 , \quad (12)$$

$$\epsilon_R(u) = \epsilon_L(u) - \tfrac{1}{2} = -0.179 \pm 0.019 , \quad (13)$$

$$\epsilon_L(d) = -\tfrac{1}{2} + \tfrac{1}{3}x + \frac{1}{r}[-\tfrac{1}{2} + \tfrac{1}{15}(3+2x)] = -0.424 \pm 0.026 , \quad (14)$$

$$\epsilon_R(d) = \epsilon_L(d) + \tfrac{1}{2} = -0.017 \pm 0.058 . \quad (15)$$

Here $x \equiv \sin^2\theta$. The first equalities are predictions of the present model; the second are experimental values.

Equations (12) and (13), and (14) and (15), may be combined to give two independent constraints on x and r:

$$-\tfrac{2}{3}x + \frac{1}{r}[\tfrac{1}{2} - \tfrac{2}{15}(3+2x)] = -0.174 \pm 0.016 , \quad (16)$$

$$\tfrac{1}{3}x + \frac{1}{r}[-\tfrac{1}{2} + \tfrac{1}{15}(3+2x)] = 0.060 \pm 0.024 . \quad (17)$$

Another important constraint on x comes from parity violation in polarized-electron–deuteron scattering:[11]

$$x = 0.224 \pm 0.020 . \quad (18)$$

[Note that $\Delta\mathscr{H}_N$ in Eq. (11) cannot contribute to parity violation observed in this experiment.] At present limits of experimental accuracy, other data, such as $e^+e^- \to \mu^+\mu^-$, W and Z masses, or neutrino-electron scattering, do not provide as strong constraints on x and r in the present model.[5] The results of a simultaneous fit to (16)–(18) are shown in Fig. 1. The contour for $\Delta\chi^2=1$ satisfies $r^{-1} < 0.15$, or

$$r > 6.7 \ . \tag{19}$$

This implies

$$\frac{M_1}{M_0} \gtrsim 0.985 \ , \tag{20}$$

$$\frac{M_2}{M_0} \gtrsim 2.1\text{–}2.5 \ . \tag{21}$$

Equation (20) is certainly in agreement with the mass of the recently discovered neutral vector boson.[12] The two numbers in Eq. (21) correspond to the two limiting cases considered by Robinett and Rosner, namely, the case in which SO(10) is broken at the Planck scale and the case in which SO(10) and SU(5) are broken at the same scale.

The coupling of the neutral boson Z_i ($i=1,2$) to the fermion f is described by the Lagrangian

$$\mathscr{L}_{Z_i,f} = \frac{e}{\sin\theta\cos\theta}\left[\frac{|M_j^2-M_0^2|}{M_2^2-M_1^2}\right]^{1/2} \bar{f}\gamma^\mu\lambda_f^{(i)} f Z_{i\mu} \ , \tag{22}$$

$$i=1,2 \rightarrow j=2,1 \ ,$$

where

$$\lambda_f^{(i)} = (I_{3L}-\sin^2\theta\, Q) + \tfrac{3}{2}\left[1-\frac{M_i^2}{M_0^2}\right](I_{3L}-Q+\tfrac{5}{3}I_{3R}) \ . \tag{23}$$

The charges I_{3L}, I_{3R}, and Q should be evaluated for the fermion f. The decay rates for Z_i to decay to fermion-antifermion pairs can be calculated from the Lagrangian (22). The important point to be stressed is that the coupling of Z_2 to the u quark is enhanced in the present model. We find that, for $M_2=2.5M_0$, $x=0.22$,

$$\frac{\Gamma(Z_2\to d\bar{d})}{\Gamma(Z_2\to u\bar{u})} = 3.5 \ , \tag{24}$$

to be compared with the corresponding ratio in the model considered by RR,

$$\left.\frac{\Gamma(Z_2\to d\bar{d})}{\Gamma(Z_2\to u\bar{u})}\right|_{\mathrm{RR}} \gtrsim 7 \ . \tag{25}$$

This has significant phenomenological implications. It means that the production of Z_2 in $\bar{p}p$ and pp collisions will be enhanced. For instance, when $M_2=2.5M_0$, the production cross section in $\bar{p}p$ collisions at $\sqrt{s}=2$ TeV is about a factor of 2 larger than that of the lightest Z_2 allowed in the model considered by RR. The relative enhancement in pp collisions at this energy is even larger.

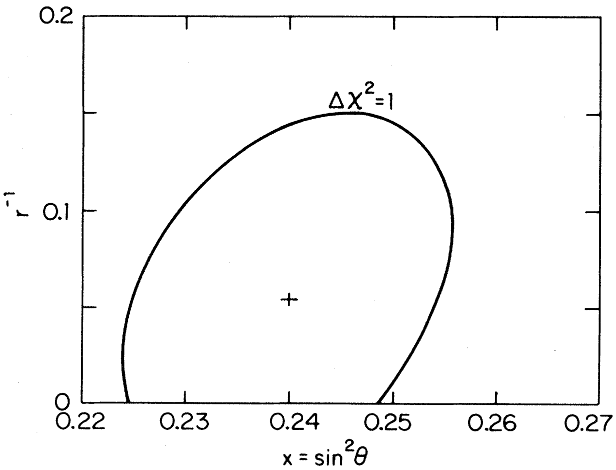

FIG. 1. Values of r and $\sin^2\theta$ from a combined fit to deep-inelastic neutrino-hadron scattering and polarized-electron–deuteron scattering data. The cross denotes the central value; $\sin^2\theta=0.240$, $r^{-1}=0.054$, $\chi^2_{\min}=1.69$.

To conclude, additional scalar fields are required to make the SO(10) model studied by RR describe fermion masses. This drastically changes the neutral-current sector of the theory. The low-energy neutrino neutral-current interactions are no longer the same as the standard model. Instead, all axial-vector-type neutral-current couplings at $q^2=0$ are identical to those in the standard model. The resulting theory reproduces more of the standard-model phenomenology. The coupling of Z_2 to $u\bar{u}$ is enhanced, making it easier to detect the Z_2 in high-energy pp and $\bar{p}p$ collisions.

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