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Is $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ a viable symmetry at low energy?

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We consider the gauge groups $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ with low-energy parity restoration and $SU(2)_L \times T_{3R} \times U_{B-L}(1)$ as alternatives to the standard model at low energies, and fit their parameters to the neutral-current data. It is shown that if present phenomenological fits to data are taken seriously, the left-right-symmetric model is disfavored because it requires *either* too small a value of $\sin^2\theta_W$ to be consistent with grand unification *or* if $\sin^2\theta_W$ is chosen at a reasonable value, it then requires an imaginary mass for one of the Z bosons. The second gauge group is consistent with data, and the best fits yield $\sin^2\theta_W \simeq 0.24$ and $M_{Z_1} = 88 \pm 8$ GeV, $M_{Z_2} \sim 230$ GeV.

I. INTRODUCTION

There has been a lot of recent interest[1–9] in alternatives to the standard Weinberg-Salam-Glashow model for electroweak unification within the framework of grand unification. One motivation is to look for experimental tests of grand unification besides proton decay. This would also signal the existence of other intermediate mass scales and populate the desert of SU(5). One popular model is the left-right-symmetric model,[1,2] $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$, which could restore parity conservation at energies as low as 100 to 200 GeV.[3] We also consider in this paper a model based on the gauge group $SU(2)_L \times T_{3R} \times U_{B-L}(1)$, where T_{3R} is the third component of the $SU(2)_R$ group, first suggested by Deshpande and Iskandar.[4] Both these models can emerge from grand unification groups such as SO(10), chiral $SU(8) \times SU(8)$, SU(16), and groups of which these are subgroups. The crucial difference between the two groups is in the value of g_R and $\sin^2\theta_W$ as determined by the renormalization group. Both these models can provide for departure from the predictions of the standard model. A feature they share is the existence of two Z bosons, and consequently a different mass for the lower Z boson from the standard model, a prospect which can soon be experimentally tested. In this paper we subject these models to a thorough examination by confronting them with low-energy data. Many authors[5–7] have already studied the low-energy phenomenology to see if consistent parameters can be found for the left-right-symmetric model which will fit all the data reasonably. Here we adopt a different philosophy. We look for the best fit to the data and see what it dictates for the parameters of the models. An unacceptable value of a parameter is then interpreted as a failure of the model; the number of standard deviations away from an acceptable value is a measure of the degree of failure. With this in mind, the data we used was chosen for its accuracy and reliability.

In Sec. II of this paper we present parametrization of the two models, and discuss the restrictions on these parameters that arise from positivity of $M_Z{}^2$ as well as from grand unification. Section III is devoted to fitting the parameters of the model to data. The failure of the left-right-symmetric model can be clearly seen. Our conclusions are presented in Sec. IV.

II. PARAMETRIZATION OF THE MODELS

In this section we present a brief review of the phenomenological analysis of the neutral-current sector that is applicable to the two models under consideration. We begin by writing the interactions in the symmetric but undiagonalized basis:

$$\mathscr{L}_{\text{int}} = g_L L_\mu J_L^\mu + g_R R_\mu J_R^\mu + g_B B_\mu J_B^\mu \; . \tag{2.1}$$

Here L_μ, R_μ, and B_μ are the gauge bosons; the currents are given by

$$J_\mu^{L,R} = \tfrac{1}{4}[\bar{u}\gamma_\mu(1\pm\gamma_5)u - \bar{d}\gamma_\mu(1\pm\gamma_5)d + \bar{\nu}\gamma_\mu(1\pm\gamma_5)\nu - \bar{e}\gamma_\mu(1\pm\gamma_5)e] \; , \tag{2.2}$$

$$J_\mu^B = \tfrac{1}{6}(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d) - \tfrac{1}{2}(\bar{\nu}\gamma_\mu \nu + \bar{e}\gamma_\mu e) \tag{2.3}$$

and g_L, g_B, and g_R are the coupling constants for the groups $SU(2)_L$, $U_{B-L}(1)$, and $SU(2)_R$ or T_{3R}, respectively. We note the essential difference between the two models is in the value of the g_R. We define a new basis to factor out electromagnetic interactions. The new currents are

$$Q_\mu = J_\mu^L + J_\mu^R + J_\mu^B$$
$$= \text{electromagnetic current} ,$$
$$J_\mu^Z = J_\mu^L - xQ_\mu$$
$$= \text{Weinberg–Salam current} , \tag{2.4}$$
$$J_\mu^Y = J_\mu^R - yQ_\mu ,$$

where x, y, and the electric charge are defined as

$$e = g_L \sin\theta_W ,$$
$$x = \sin^2\theta_W$$
$$= g_R{}^2 g_B{}^2/(g_B{}^2 g_L{}^2 + g_B{}^2 g_R{}^2 + g_L{}^2 g_R{}^2) , \tag{2.5}$$
$$y = x(g_L{}^2/g_R{}^2) .$$

The interaction Lagrangian now becomes

$$\mathscr{L}_{\text{int}} = eA_\mu Q^\mu + (g_L/\cos\theta_W) Z_\mu J_Z^\mu + (g_R{}^2 + g_B{}^2)^{1/2} C_\mu \left[\left[\frac{g_L \tan\theta_W}{g_R} \right]^2 J_Z^\mu + J_Y^\mu \right] . \tag{2.6}$$

The photon field A_μ, as well as the fields Z_μ and C_μ, are linear combinations of L_μ, R_μ, and B_μ. Additional details of these transformations are found in Ref. 8. The advantage of the representation equation (2.6) is that the first two terms correspond to the standard model, while the last term is the correction arising from the additional group. The fields Z and C are not mass eigenstates, and we allow an arbitrary mixing among them. The general mass matrix is defined by

$$M^2 = \begin{bmatrix} M_Z{}^2 & M_{Z-C}{}^2 \\ M_{Z-C}{}^2 & M_C{}^2 \end{bmatrix} . \tag{2.7}$$

We can then write an effective interaction at low q^2 as[4]

$$\mathscr{L}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} (\eta_L J_\mu^Z J_Z^\mu - 2\eta_{LR} J_\mu^Z J_Y^\mu + \eta_R J_\mu^Y J_Y^\mu) , \tag{2.8}$$

where

$$\eta_L = \rho[1 + \alpha^2(1+\beta\gamma^2)^2] ,$$
$$\eta_{LR} = -\rho\alpha^2\beta(1+\beta\gamma^2) , \tag{2.9}$$
$$\eta_R = \rho\alpha^2\beta^2$$

and

$$\rho = \left[\frac{g_L{}^2}{8M_Z{}^2\cos^2\theta_W} \right] \Big/ \left[\frac{G_F}{\sqrt{2}} \right] ,$$
$$\alpha^2 = M_{Z-C}{}^4/\det M^2 ,$$
$$\beta = -\left[\frac{(g_R{}^2 + g_B{}^2)}{(g_L{}^2 \sec^2\theta_W)} \right]^{1/2} \frac{M_Z{}^2}{M_{Z-C}{}^2} , \tag{2.10}$$
$$\gamma^2 = (g_L \tan\theta_W/g_R)^2 .$$

In the most general case there are five independent parameters in Eq. (2.8). These are x, y, η_L, η_{LR}, and η_R which can be traced to three unknowns in the mass matrix and two unknown coupling constants (since e is determined). However, for either of the two models we shall consider there is one more constraint among the coupling constants arising from grand unification and the renormalization group. In the case of $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$, if this is a low-energy symmetry, by which we mean that all gauge bosons are lighter than 1 TeV, then the coupling g_L and g_R should evolve in the same way. This implies their equality. In the second model we shall assume that the grand unified group breaks at $\sim 10^{15}$ GeV leaving $SU(2) \times T_{3R} \times U_{B-L}(1)$ as the gauge group. Here T_{3R} is the third component of the $SU(2)_R$. Now the two U(1) groups evolve in the same way. Since the currents are normalized differently we shall have $g_R = g_B(\frac{2}{3})^{1/2}$. After some simple algebra we have

$$y = x \quad \text{for } SU(2)_L \times SU(2)_R \times U_{B-L}(1) \tag{2.11}$$

and $(g_R/g_L)^2 = 5\tan^2\theta_W/3$, which in turn implies

$$y = 3(1-x)/5 \quad \text{for } SU(2)_L \times T_{3R} \times U_{B-L}(1) . \tag{2.12}$$

There are additional constraints on the parameters. From positivity of the diagonalized masses M_1 and M_2 of the neutral gauge bosons, as well as from definition in Eq. (2.9), we have

$$\eta_L > 0, \quad \eta_R > 0 , \tag{2.13}$$
$$\left[\frac{38.6\text{ GeV}}{M_1} \right]^2 + \left[\frac{38.6\text{ GeV}}{M_2} \right]^2 = x[(1-x)(\eta_L + \eta_R) + 2x\eta_{LR}] , \tag{2.14}$$
$$\left[\frac{38.6\text{ GeV}}{M_1} \right] \left[\frac{38.6\text{ GeV}}{M_2} \right] = x^2(1-2x)(\eta_L\eta_R - \eta_{LR}{}^2) , \tag{2.15}$$

where we have used

$$xM_W{}^2 = \alpha(M_W{}^2)\pi/\sqrt{2}G_F = (38.6\text{ GeV})^2 \tag{2.16}$$

with the value of $\alpha^{-1}(M_W{}^2) = 128$ from renormalization-group analysis. We shall show that $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ has great difficulty in satisfying these constraints. There are further constraints on allowed values of the parameters $x = \sin^2\theta_W$. In the model $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ with minimal Higgs structure there is strict inequality:

$$\tfrac{1}{4} < x < \tfrac{3}{8} , \tag{2.17}$$

while for $SU(2)_L \times T_3(R) \times U_{B-L}(1)$ the restriction is the same as in SU(5):

$$\tfrac{1}{6} < x < \tfrac{3}{8} . \tag{2.18}$$

A detailed study by Rizzo[9] in which effects of Higgs bosons and fermions are taken into account shows that the preferred value of x is

$$x = 0.27\text{–}0.28 \text{ for } SU(2)_L \times SU(2)_R \times U_{B-L}(1) .$$

For the $SU(2)_L \times T_3(R) \times U_{B-L}(1)$ the preferred value is the same as SU(5),[10] namely, $x \leq 0.216$ for $SU(2)_L \times T_3(R) \times U_{B-L}(1)$. Determined values of x also can be used to test the plausibility of a model.

As is well known, low-energy data can be described by ten model-independent parameters. We adopt the following convention for these parameters.

(a) Quark-neutrino interaction:

$$\mathscr{L}_{\nu\text{-}q} = -\frac{G_F}{\sqrt{2}}[\bar{\nu}\gamma_\mu(1+\gamma_5)\nu][u_L\bar{u}\gamma_\mu(1+\gamma_5)u + u_R\bar{u}\gamma_\mu(1-\gamma_5)u + d_L\bar{d}\gamma_\mu(1+\gamma_5)d + d_R\bar{d}\gamma_\mu(1-\gamma_5)d] . \tag{2.19}$$

(b) Electron-neutrino interaction:

$$\mathscr{L}_{e\text{-}\nu} = -\frac{G_F}{\sqrt{2}}[\bar{\nu}\gamma_\mu(1+\gamma_5)\nu][\bar{e}\gamma^\mu(g_V + g_A\gamma_5)e] . \tag{2.20}$$

(c) Quark-electron interactions:

$$\mathscr{L}_{e\text{-}q} = -\frac{G_F}{\sqrt{2}}\{\bar{e}\gamma^\mu e[\epsilon_{VA}(u)\bar{u}\gamma_\mu\gamma_5 u + \epsilon_{VA}(d)\bar{d}\gamma_\mu\gamma_5 d] + \bar{e}\gamma^\mu\gamma_5 e[\epsilon_{AV}(u)\bar{u}\gamma_\mu u + \epsilon_{AV}(d)\bar{d}\gamma_\mu d]\} . \tag{2.21}$$

The relationship between the model parameters and the model-independent parameters is summarized in Table I.

III. DETERMINATION OF MODEL PARAMETERS

The parameters x, η_L, η_{LR}, and η_R were evaluated for both the models using a least-squares fit to the neutral-current data. The values we used for the neutrino couplings to quarks and leptons, u_L, u_R, d_L, d_R, g_V, and g_A, were those obtained in the analysis of Langacker *et al.*[11] Unfortunately such an analysis is not available for the parity-violating electron-quark couplings $\epsilon_{VA}(u)$, $\epsilon_{VA}(d)$, $\epsilon_{AV}(u)$, and $\epsilon_{AV}(d)$. We use instead some linear combinations of these couplings that are determined from electron-deuteron asymmetry, and from atomic-physics experiments on bismuth. Hung and Sakurai[12] have analyzed the SLAC (Ref. 13) data on electron-

TABLE I. Relations between model-independent neutral-current couplings and model parameters. To recover the standard-model expressions, set $\eta_L = 1$ and $\eta_R = \eta_{LR} = 0$.

Parameters	$SU(2)_L \times SU(2)_R \times U_{B-L}(1)$	$SU(2)_L \times T_{3R} \times U_{B-L}(1)$
u_L	$\frac{1}{2}\eta_L - \frac{2}{3}x(\eta_L - \eta_{LR})$	$\frac{1}{2}\eta_L + \frac{2}{5}\eta_{LR} - \frac{2}{3}x(\eta_L + \frac{3}{5}\eta_{LR})$
u_R	$-\frac{1}{2}\eta_{LR} - \frac{2}{3}x(\eta_L - \eta_{LR})$	$-\frac{1}{10}\eta_{LR} - \frac{2}{3}x(\eta_L + \frac{3}{5}\eta_{LR})$
d_L	$-\frac{1}{2}\eta_L + \frac{1}{3}x(\eta_L - \eta_{LR})$	$-\frac{1}{2}\eta_L - \frac{1}{5}\eta_{LR} + \frac{1}{3}x(\eta_L + \frac{3}{5}\eta_{LR})$
d_R	$\frac{1}{2}\eta_{LR} + \frac{1}{3}x(\eta_L - \eta_{LR})$	$\frac{3}{10}\eta_{LR} + \frac{1}{3}x(\eta_L + \frac{3}{5}\eta_{LR})$
g_A	$-\frac{1}{2}(\eta_L + \eta_{LR})$	$-\frac{1}{2}(\eta_L + \eta_{LR})$
g_V	$(2x - \frac{1}{2})(\eta_L - \eta_{LR})$	$-\frac{1}{2}\eta_L - \frac{7}{10}\eta_{LR} + 2x(\eta_L + \frac{3}{5}\eta_{LR})$
$\epsilon_{AV}(u)$	$(\frac{4}{3}x - \frac{1}{2})(\eta_L - \eta_R)$	$(\frac{4}{3}x - \frac{1}{2})(\eta_L + \frac{8}{5}\eta_{LR} + \frac{3}{5}\eta_R)$
$\epsilon_{AV}(d)$	$(\frac{1}{2} - \frac{2}{3}x)(\eta_L - \eta_R)$	$\frac{2}{3}(\eta_L + \eta_{LR}) - (\frac{1}{6} + \frac{2}{3}x)(\eta_L + \frac{8}{5}\eta_{LR} + \frac{3}{5}\eta_R)$
$\epsilon_{VA}(u)$	$(-\frac{1}{2} + 2x)(\eta_L - \eta_R)$	$\frac{2}{3}(\eta_L + \eta_{LR}) - (\frac{7}{6} - 2x)(\eta_L + \frac{8}{5}\eta_{LR} + \frac{3}{5}\eta_R)$
$\epsilon_{VA}(d)$	$-\epsilon_{VA}(u)$	$-\epsilon_{VA}(u)$

deuteron scattering and found

$$A_1 \equiv \tfrac{2}{3}\epsilon_{AV}(u) - \tfrac{1}{3}\epsilon_{AV}(d) = -0.30 \pm 0.08\ ,$$
$$A_2 \equiv \tfrac{4}{3}\epsilon_{AV}(u) - \tfrac{2}{3}\epsilon_{AV}(d) + \tfrac{1}{3}\epsilon_{VA}(u) - \tfrac{1}{6}\epsilon_{VA}(d) = -0.53 \pm 0.05\ . \tag{3.1}$$

The value of Q_W from the most recent Seattle experiment[14] yields the value

$$A_3 \equiv \epsilon_{AV}(u) + 1.15\epsilon_{AV}(d) = 0.20 \pm 0.03\ . \tag{3.2}$$

To make the least-squares fit more tractable, we first linearized the equations in Table I so matrix methods[15] could be used to find the four model parameters and their uncertainties. This was done by considering the parameters as a zeroth-order approximation plus a small correction term and then expanding the equations to first order in these corrections. The zeroth-order approximations were determined by analyzing the neutrino scattering data and the parity-violating electron-quark data separately. This was possible to do because, treated separately, both sectors could be linearized without expanding parameters. We used the average of the two values for our zeroth-order approximation. As a check on our procedure we noted that after linearizing all the equations and treating them together, the corrections to the parameters were indeed small.

The experimental values used in our analysis as well as our best fits to either model are listed in Table II. Here we also list the best fits found by Sehgal[6] and Bajaj and Rajasekaran.[7]

From the least-squares fit for the gauge model $SU_L(2) \times T_{3R} \times U_{B-L}(1)$ we find the four parameters to be

$$x = 0.243 \pm 0.015,\quad \eta_L = 1.08 \pm 0.08\ ,$$
$$\eta_{LR} = -0.057 \pm 0.09,\quad \eta_R = 0.15 \pm 0.14\ . \tag{3.3}$$

One can then calculate the masses of the two neutral bosons from Eqs. (2.14) and (2.15) and we find

$$M_{Z_1} = 88 \pm 8\ \text{GeV},\quad M_{Z_2} \gtrsim 230\ \text{GeV}\ . \tag{3.4}$$

The uncertainty for the heavier mass is quite large due to its sensitive dependence on η_R.

For the gauge model $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ the situation is not so encouraging. We obtain for the model parameters

$$x = 0.246 \pm 0.013,\quad \eta_L = 1.03 \pm 0.06\ ,$$
$$\eta_{LR} = -0.01 \pm 0.07,\quad \eta_R = -0.06 \pm 0.11\ . \tag{3.5}$$

The value of x is several standard deviations below the predicted value from the renormalization-group equations, i.e., $x \approx 0.27$—0.28. What is even worse is that there is a correlation between the values of x and η_R such that if we take the upper range for x, we are forced into the lower range for η_R, which violates the positivity constraint on it. Further, as x becomes larger, there is no way to reconcile the data from electron-deuteron scattering and atomic-physics experiments on bismuth. We therefore assumed for the sake of argument that the atomic-physics data was in error since it tends to favor small x and since there may still be some atomic effects not treated properly in calculating $Q_W(\text{Bi})$. We then fixed the value of x at 0.27 and 0.28 and fitted the rest of the parameters to the data without using the value for A_3 from $Q_W(\text{Bi})$. (We display the best fit for $x = 0.27$ in Table II.) In both cases, however, we found that the parameter η_R was negative by more than two standard deviations, which is in gross disagreement with the positivity constraint on it:

$$x = 0.27,\quad \eta_R = -0.32 \pm 0.14\ ,$$
$$x = 0.28,\quad \eta_R = -0.43 \pm 0.15\ . \tag{3.6}$$

TABLE II. Experimental values of model-independent parameters used by us, with best fits to both $SU_L(2) \times SU_R(2) \times U(1)$ and $SU_L(2) \times T_{3R} \times U(1)$ models. We also present the fits obtained by Sehgal (S) (Ref. 6), and Bajaj and Rajasekaran (BR) (Ref. 7) for the left-right-symmetric model as well as a second fit made by us without using A_3 as input and fixing $\sin^2\theta_W = 0.27$. For completeness we include a fit to the Weinberg-Salam (WS) standard model, $SU(2) \times U(1)$.

	$SU_L(2)\times SU_R(2)\times U(1)$				$SU_L(2)\times T_{3R}\times U(1)$	WS
Experiment	Best fit	$x=0.27$	S (Ref. 6)	BR (Ref. 7)	Best fit	$x=0.234$
$u_L = 0.340 \pm 0.033$	0.344	0.330	0.325	0.347	0.348	0.343
$u_R = -0.179 \pm 0.019$	-0.166	-0.17	-0.15	-0.143	-0.164	-0.157
$d_L = -0.424 \pm 0.026$	-0.430	-0.436	-0.421	-0.444	-0.444	-0.422
$d_R = -0.017 \pm 0.058$	0.08	0.066	0.054	0.046	0.068	0.078
$g_A = -0.52 \pm 0.06$	-0.51	-0.50	-0.48	-0.49	-0.51	-0.50
$g_V = 0.06 \pm 0.08$	-0.008	0.046	0	-0.012	0.008	-0.03
$A_1 = -0.30 \pm 0.08$	-0.25	-0.28	-0.27	-0.25	-0.24	-0.24
$A_2 = -0.53 \pm 0.05$	-0.50	-0.53	-0.53	-0.50	-0.50	-0.50
$A_3 = 0.20 \pm 0.03$	0.23	(0.32)	(0.26)	0.23	0.19	0.21

Once again we are faced with the prediction of an unphysical parameter (which would this time require an imaginary mass for one of the neutral bosons). The data seem to clearly disfavor the left-right-symmetric model with a low-mass right-handed boson.

It should be pointed out that several authors have made fits for the left-right-symmetric model using parameter-search methods. Rizzo and Senjanović[5] have fit the data to within 1.5 standard deviations for several values of the parameters; however, they appear not to have imposed the most stringent requirement from electron-deuteron scattering, namely the linear combination we call A_2, which is determined more precisely than individual ϵ parameters. Since η_R depends solely on the ϵ parameters, it is crucial to use the most precise experimental values to determine its magnitude. Sehgal[6] has given the following set of parameters without using A_3 from Q_W(Bi):

$$\begin{aligned} &x = 0.25 \pm 0.02, \quad \eta_L = 1.0 \pm 0.06 \,, \\ &\eta_{LR} = -0.05 \pm 0.06, \quad \eta_R = -0.2 \pm 0.2 \,. \end{aligned} \tag{3.7}$$

Here x is again too small by one standard deviation and η_R is also negative by one standard deviation. In addition, Eq. (2.15) for the mass eigenvalues is negative unless one takes both η_R and η_{LR} to be equal to zero. This would then make one of the bosons infinitely heavy while the lighter one would have a mass of 86 ± 3 GeV. We are essentially back to the standard model. An earlier fit was done by Bajaj and Rajasekaran[7] using numbers obtained by Ecker.[16] Their results, which use the positivity of η_R, also support our conclusion.

Recently, Fogelman and Rizzo[17] have pointed out that the value of x in the $SU(2)_L \times T_3(R) \times U_{B-L}(1)$ model is higher than expected, if this group emerges from SO(10). The proton lifetime would then be less than the experimental limit. However, this argument is not too compelling because this model could arise from other models of grand unification, like the chiral SU(8) model,[18] where the proton is stable. Another way of raising the value of x theoretically is to put an intermediate scale at M_R, where $SU(2)_R$ gets broken to $T_3(R)$, with M_R between M_W and the unification scale M_x. This possibility will be considered in a forthcoming publication.[19] Making SO(10) supersymmetric can also change the value of x and proton lifetime in the correct direction as in the case of SU(5).[20] This effect on the left-right-symmetric model would, however, make x even larger thus forcing η_R even more negative.

A related observation made recently[21] is that if one implements Dine-Fischler-Srednicki mechanism[22] in SO(10) to resolve the strong *CP* problem with an invisible axion, then certain patterns of symmetry breaking are not allowed. In particular $SO(10) \to SO(6) \times SO(4)$ necessary to obtain $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ as a low-energy group seems not to be allowed, while $SO(10) \to SU(5) \times U(1) \to SU(3) \times SU(2) \times U(1) \times U(1)$ is allowed.

IV. CONCLUSIONS

We have examined alternatives to the standard model which could well arise from grand unified models which are larger than SU(5). The two most plausible structures at low energy are $SU(2)_L \times T_3(R) \times U_{B-L}(1)$ and $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$. The former yields an excellent fit to all low-energy phenomena, and the values of $\sin^2\theta_W$ are consistent with grand unification. The masses of the two Z bosons of the theory are

$$\begin{aligned} &M_{Z_1} = 88 \pm 8 \text{ GeV} \,, \\ &M_{Z_2} \gtrsim 230 \text{ GeV} \,. \end{aligned} \tag{4.1}$$

Since the mass of the lighter Z boson differs from that in the Weinberg-Salam model, it will be possible to detect this in the near future.

We have carried out a least-squares fit to the data for $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$ model, and found that the data require *either* too small a value for $\sin^2\theta_W$, *or* if atomic-physics experiments are disregarded and $\sin^2\theta_W$ is chosen from grand unification, the value of η_R was negative by two standard deviations, forcing one of the Z bosons to have an imaginary mass. We therefore find this model rather unlikely to be a low-energy symmetry of the theory.

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