Seeking Signs of a Second Z

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(Received 17 November 1989)

Principles of minimality and unifiability lead us to a unique family of mutants of the electroweak theory which are parametrized solely by the mass of a heavy Z' boson. These models generate an additional vectorial current-current interaction at low energy, and modify the properties of the observed Z boson in a way that would appear (in the context of the standard model) as an apparently fractional number (exceeding three) of light neutrino species. Such alternative theories offer a foil against which to test our confidence in the orthodox theory.

PACS numbers: 12.15.Cc, 14.80.Er

Experimental data confirm the predictions of the electroweak theory to a precision of a few percent. Our aim is to exhibit a plausible one-parameter family of alternative models whose predictions coincide with those of the standard theory as the parameter approaches zero. We examine a class of anomaly-free models based on the extended gauge group

$$\mathcal{G} = \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)\times\mathrm{U}(1)' \tag{1}$$

in which there is a second and heavier Z' boson. Each fermion family is to transform identically under $\mathcal{G}$. We are guided by principles of minimality and of unifiability. The customary family of fifteen chiral fermions admits no anomaly-free current beyond those present in SU(5). For there to be a U(1)$'$, and hence a Z', the family must be extended: Its minimal extension, the one we adopt, involves the introduction into each family of an additional fermion $\tilde{\nu}$ transforming trivially under conventional SU(3)×SU(2)×U(1). The additional anomaly-free current corresponds to $B-L$. In a unifiable theory, the generator of the U(1)$'$ current must be orthogonal to those corresponding to weak hypercharge and isospin, which $B-L$ is not. Without loss of generality, we choose the appropriate generator of the U(1)$'$ current to be

$$Y' = 5(B-L) - 4Y. \tag{2}$$

To implement our minimality principle, we assume all Higgs bosons to be either weak singlets or doublets with quantum numbers such that they could have Yukawa couplings to fermions. Thus, the Higgs sector includes one or more weak doublets (ϕ^+,ϕ^0) for which $Y' = -2$. These particles couple both to leptons and to quarks. When ϕ^0 develops a vacuum expectation value (VEV), masses are generated for all quarks and leptons, including Dirac neutrino masses. An additional Higgs boson χ^0 is assigned $Y' = -10$ and is invariant under the conventional gauge group. It has bilinear Yukawa couplings to the $\tilde{\nu}$ states. We assign it a VEV larger than that of ϕ^0 to generate a large mass for Z' and large Majorana masses for the three singlet "neutrinos." Small Majorana masses are induced via the see-saw mechanism for conventional neutrino states. The Higgs doublet(s) breaks the conventional electroweak group and leaves $B-L$ intact; the singlet breaks $B-L$ but not the electroweak group. No other type of Higgs multiplet is introduced. An elegant consequence of this pattern of symmetry breaking appears in our subsequent discussion of the low-energy limit of our model.

We might try to constraint this theory by appealing to known limits on neutrino masses. Such arguments would depend upon hypotheses regarding the unknown values of the Yukawa couplings of ϕ and χ responsible for the neutrino mass matrix. Instead, we compute the perturbations induced by the new gauge interaction upon the standard-model predictions for the properties of the Z boson and for neutral-current phenomena. We use the empirical fact that induced Majorana neutrino masses are "small" to justify our neglect of mixing between conventional (doublet) neutrinos and their heavy (singlet) counterparts.

Define the (index-suppressed) neutral gauge couplings to be

$$gW_3\bar{\psi}T_3\gamma\psi + g'W_4\bar{\psi}Y\gamma\psi + g_2W_5\bar{\psi}Y'\gamma\psi. \tag{3}$$

The quantum-number assignments following from (2) are displayed below:

	u_L	d_L	u_R	d_R	ν_L	e_L	$\tilde{\nu}_R$	e_R	ϕ^+	ϕ^0	χ^0
T_3	$+\frac{1}{2}$	$-\frac{1}{2}$	0	0	$+\frac{1}{2}$	$-\frac{1}{2}$	0	0	$+\frac{1}{2}$	$-\frac{1}{2}$	0
Y	$+\frac{1}{6}$	$+\frac{1}{6}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	-1	$+\frac{1}{2}$	$+\frac{1}{2}$	0
Y'	$+1$	$+1$	-1	$+3$	-3	-3	-5	-1	-2	-2	-10

The fermionic and gauge sectors of this theory are identical with those of the "χ model" (without the supersymmetric partners) studied by Gonzalez-Garcia and Valle,[1] by del Aguila, Quirós, and Zwirner,[2] by Amaldi *et al.*,[3] and by Durkin and Langacker,[4] who in turn base their analyses on the work of Robinett and Rosner[5] and Leung and Rosner.[6] All but the first two of these works consider different or more general Z mass matrices than the one we are led to, due to different assumptions (or lack thereof) about the Higgs sector. Our specific choice of a Higgs sector for the theory leads to a one-parameter family of models with naturally light neutrinos. Gonzalez-Garcia and Valle along with del Aguila Quirós, and Zwirner consider the same mass matrix as we do (when their parameter $\beta \rightarrow 0$) but study different implications of the theory. Leung and Rosner[6] use a $Y' = -5$ scalar in place of our χ^0 are arrive at several expressions equivalent to ours. However, our model has the advantage of generating large Majorana masses for the right-handed neutrinos and hence naturally predicting small masses for the observed left-handed neutrinos.

The coupling constants g and g' are defined as usual. We ignore radiative corrections in this work and define the weak mixing angle by $g' \equiv g \tan\theta$. Our modified electroweak theory is supposed to arise from a simple gauge broken at the unification mass scale. Sine both U(1)'s "run" the same, we expect $g_2^2 \operatorname{Tr} Y'^2 = g'^2 \operatorname{Tr} Y^2$, and hence

$$g_2^2 = g'^2/24 . \tag{4}$$

Equations (2) and (4) comprise our appeal to unifiability. Denote the VEV's of ϕ and χ by $u/\sqrt{2}$ and $v/\sqrt{2}$, and define the useful notation $g_1 \equiv (g^2+g'^2)^{1/2} = g/\cos\theta$ and $s \equiv \sin^2\theta$. The W mass is unaffected by U(1)$'$ and remains $M_W^2 = g^2u^2/4$. The masses of the two neutral weak intermediaries and their mixing are determined by the two-by-two matrix,

$$\mathcal{M}^2 = \begin{pmatrix} g_1^2u^2/4 & g_1g_2u^2 \\ g_1g_2u^2 & g_2^2(100v^2+4u^2) \end{pmatrix} , \tag{5}$$

which acts between Z^0 ($\equiv W_3\cos\theta - W_4\sin\theta$) and W_5. For the heavier eigenstate Z', we find to lowest nonvanishing order in u^2/v^2 the eigenvalue

$$M_{Z'}^2 = 100 g_2^2 v^2 . \tag{6}$$

To discuss the manner in which the predictions of our extended gauge theory depart from those of the standard model, we introduce the positive perturbative parameter

$$\lambda \equiv \frac{3}{50s}\frac{u^2}{v^2} = \left(\frac{M_Z}{M_{Z'}}\right)^2 , \tag{7}$$

where the last equality holds to lowest order if (4) is valid. The mass of the Z is modified, and we find the lighter eigenvalue to be

$$M_Z^2 = \frac{g_1^2u^2}{4}[1 - \tfrac{2}{3}\lambda s + O(\lambda^2)] . \tag{8}$$

Also to lowest order in λ, the corresponding lighter Z eigenstate is

$$Z = Z^0 - \left(\frac{g_1}{g_2}\right)\left(\frac{\lambda s}{6}\right) W_5 , \tag{9}$$

while the heavier eigenstate is given by

$$Z' = W_5 + \left(\frac{g_1}{g_2}\right)\left(\frac{\lambda s}{6}\right) Z^0 . \tag{10}$$

The gauge couplings to these mass eigenstates become

$$\frac{e}{\sin\theta\cos\theta} Z\bar{\psi}[T_3 - Qs - \tfrac{1}{6}\lambda s Y']\gamma\psi + g_2 Z'\bar{\psi}Y'\gamma\psi , \tag{11}$$

with the neglect of $O(\lambda)$ corrections to the Z' couplings.

Our modification of the standard model changes the anticipated properties of the observed Z boson. We focus on its partial decay widths, which may be written[7] as

$$\Gamma_i = (CG_F M_{Z^0}^2 M_Z/6\pi\sqrt{2})[V_i^2 + A_i^2] , \tag{12}$$

where C is a QCD factor equal to unity for leptons and to $3+O(\alpha_s)$ for quarks. The factor of M_Z comes from phase space and is the physical Z mass, while the factor $G_F M_{Z^0}^2$ stands for the known combination of the coupling constants $\sqrt{2}e^2/8\sin^2\theta\cos^2\theta$. We may insert into (12) the expression $M_{Z^0}^2 = (1+\frac{2}{3}\lambda s)M_Z^2$ following from (8) to obtain

$$\Gamma_i = (1+\tfrac{2}{3}\lambda s)(CG_F M_Z^3/6\pi\sqrt{2})[V_i^2+A_i^2] , \tag{13}$$

so that the partial widths are related directly to the cube of the physical Z mass. The departures of the various Γ_i from their standard-model values arise from two distinct sources: from the overall factor in (13) and from the modifications of the V_i and A_i coefficients for Z determined by (11).

We exhibit below the sum of $V_i^2 + A_i^2$ appropriate to the total hadronic partial width Γ_H (where we include the color factor, assume that the top-quark channel is closed, neglect phase-space corrections due to finite quark masses, and omit all radiative corrections):

$$C \sum_{\text{quarks}} (V_i^2+A_i^2) = \tfrac{15}{2} - 14s + \tfrac{44}{3}s^2 + \lambda s(1-8s) . \tag{14}$$

The corresponding sum appropriate to the total charged-lepton partial width, $\Gamma_e + \Gamma_\mu + \Gamma_\tau$, is

$$\sum_{e,\mu,\tau} (V_i^2+A_i^2) = \tfrac{3}{2} - 6s + 12s^2 + \lambda s(-3+8s) . \tag{15}$$

For $3+\Delta$ neutrino species, the sum appropriate to Γ_ν is given by

$$\sum_{\nu_i} (V_i^2+A_i^2) = (3+\Delta)(\tfrac{1}{2} + \lambda s) . \tag{16}$$

Finally, the sum over all quarks and leptons of the squares of the coupling constants is just the sum of (14), (15), and (16):

$$\sum_{\rm all} C(V_i^2+A_i^2) = \tfrac{21}{2} - 20s + \tfrac{80}{3}s^2 + \lambda s + \Delta(\tfrac{1}{2}+\lambda s)\,. \tag{17}$$

We insert the empirical value $s=0.23$ into (13)–(17) to obtain experimental predictions. (This value of s results from a fit[7] to the standard model. Better, but considerably more difficult, would be to fit all available data to the model we consider.) The total width of the Z is determined by (13) and (17) to be

$$\Gamma = \Gamma^0(1+0.185\lambda+0.068\Delta+0.042\lambda\Delta)\,. \tag{18}$$

The hadronic cross section at the Z peak at the CERN e^+e^- collider LEP and the SLAC Linear Collider (SLC) is modified because of the departure from the standard-model prediction of the following combination of partial widths, to which it is proportional:

$$\frac{\Gamma_e\Gamma_H}{\Gamma^2} = \frac{\Gamma_e^0\Gamma_H^0}{(\Gamma^0)^2}(1-0.45\lambda-0.137\Delta-0.063\lambda\Delta)\,. \tag{19}$$

These leptonic branching ratios may also be useful:

$$\frac{\Gamma_e}{\Gamma_H} = \frac{\Gamma_e^0}{\Gamma_H^0}(1-0.31\lambda)\,,$$
$$\frac{\Gamma_\nu}{\Gamma_e} = \frac{\Gamma_\nu^0}{\Gamma_e^0}(1+0.81\lambda+0.33\Delta+0.153\lambda\Delta)\,. \tag{20}$$

In all of these expressions the superscript 0 on the partial or total width indicates the standard-model value calculated using the standard-model couplings (for three fermionic families with a closed top channel) and the experimentally measured Z mass.

We have not fit our results to preliminary data recently announced by SLC and by LEP. However, measurements of the total width Γ (18) and of the peak cross section (19) would both coincidentally constrain a similar linear combination of Δ and λ, roughly $\Delta+3\lambda$ when both are small. [Curiously, the same coincidence applies to a measurement of the neutrino branching ratio, although it certainly does not apply to the muonic branching ration (20).] Thus, an apparently fractional neutrino number (in excess of three, since λ is necessarily positive) may be more rationally interpreted as evidence for the models we consider. For example, a hypothetically observed value $\Delta\simeq 0.3$ would correspond to $\lambda\simeq 0.1$ and $M_{Z'}\simeq 300$ GeV.

To calculate the effects of U(1)′ at very low energies, that is, the various four-fermion terms in the effective Lagrangian, we simply invert the mass matrix (5) and multiply it by (J_1,J_2) on the left and by $(J_1,J_2)^T$ on the right, where $J_1 = g_1\bar\psi(T_3-Qs)\gamma\psi$ and $J_2 = g_2\bar\psi Y'\gamma\psi$ are the currents that couple to Z^0 and W_5, respectively. To all orders in λ the result for the effective four-fermion neutral-current interaction is

$$\frac{8G_F}{\sqrt2}\left([\bar\psi(T_3-Qs)\gamma\psi]^2+\tfrac{2}{3}\lambda s\{\bar\psi[Q(1-s)-\tfrac{5}{4}(B-L)]\gamma\psi\}^2\right). \tag{21}$$

The first term in (21) is the conventional neutral-current interaction. The net effect of the U(1)′ couplings at low energies is to generate a second form of current×current interaction. Remarkably but not surprisingly, the new interaction involves a purely vectorial current, a linear combination of $B-L$ and Q with no chiral admixture. (This observation was also made by Leung and Rosner.[6]) To see why this must be, note that the new interaction must be proportional to λ since it must vanish when λ vanishes and the Z' becomes infinitely massive. In the opposite extreme, as $v\to 0$ and $\lambda\to\infty$ the new interaction dominates over the weak interaction, and the square of the gauge-boson mass must be replaced by k^2 as is appropriate for the exchange of a massless gauge boson. This is precisely the limit in which both $B-L$ and Q (and only these) are unbroken symmetries. The new interaction must involve a current that would be conserved in this limit; hence a linear combination of these, and hence a vectorial current. Had we chosen a model with additional Higgs doublets whose VEV's break $B-L$ (which therefore cannot couple to fermions), this proof would fail because no second photon would appear in the $v\to 0$ limit. Our choice of a Higgs sector is the minimal one necessary to obtain both masses for all fermions and a purely vectorial new interaction at low energy. As a consequence of the vectorial nature of the new interaction, the standard-model results for atomic and nuclear parity violation remain intact. However, the neutrino-quark and neutrino-lepton parameters are changed in the following manner, with the notation of the Particle Data Group:[7]

$$\begin{aligned}
\epsilon_L^u &= \tfrac12 - \tfrac23 s + \lambda s(\tfrac{5}{12} - \tfrac{10}{9}s)\,,\\
\epsilon_L^d &= -\tfrac12 + \tfrac13 s + \lambda s(-\tfrac54 + \tfrac59 s)\,,\\
\epsilon_R^u &= -\tfrac23 s + \lambda s(\tfrac{5}{12} - \tfrac{10}{9}s)\,,\\
\epsilon_R^d &= \tfrac13 s + \lambda s(-\tfrac54 + \tfrac59 s)\,,\\
g_V^e &= -\tfrac12 + 2s + \lambda s(\tfrac56 + \tfrac{10}{3}s)\,.
\end{aligned} \tag{22}$$

The newly induced neutrino couplings are vectorial for quarks and for charged leptons. Neither the $C_{iu,d}$ coefficients nor g_A^e are affected by the new interaction because they are axial.

A cursory glance at the data[7] on neutral-current phenomena indicates the apparent adequacy of orthodox electroweak theory, and suggests the limit $\lambda\le 0.1$. However, we have not sought a best fit (to both the low-energy data and the Z-boson properties now being measured at SLC and LEP) with both s and λ treated as free parameters. A neutrino count at LEP to an accuracy of

0.1 neutrino can reveal a Z' boson up to a mass of 500 GeV. We also note that a limit on λ may be set from the failure to find the Z' boson at existing hadron colliders (the next generation of hadron colliders should set an even better limit) and from the behavior of the lepton asymmetry both at the intermediate energies now available at the KEK collider TRISTAN, and at the highest energies to become available at LEP. Since the only argument favoring the standard electroweak theory is its simplicity, we regard the comparison of our variant models with experiment to be essential.

This research was supported in part by the National Science Foundation under Grant No. PHY-87-14654.

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