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New-Z' phenomenology

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We show that $L_1=L_e-L_\mu$, $L_2=L_e-L_\tau$, and $L_3=L_\mu-L_\tau$ (where $L_{e,\mu,\tau}$ are the family lepton numbers) are anomaly free and can thus be gauged. Three simple theories featuring a flavor-conserving second Z boson ($Z'_{1,2,3}$) result. Bounds on the Z'_i coupling constant (g'_i) and mass are derived. The mass of Z'_1 has a lower bound of 60–150 GeV at 90% confidence level for reasonable values of g'_1. The mass of Z'_2 has a best-fit value of about 60 GeV. The physics of these bosons in the KEK TRISTAN and CERN LEP window of 63–87 GeV is discussed. Constraints on Z'_3 interactions are derived from $(g-2)_\mu$.

Because of the absence of right-handed neutrinos, the three-generation minimal standard model (MSM) Lagrangian is invariant under the three global symmetries of family lepton number: $U(1)_{L_e}$, $U(1)_{L_\mu}$, and $U(1)_{L_\tau}$. These symmetries are present for all choices of the Yukawa coupling constants. Although some effort has been put into the search for family lepton-number-violating processes, none have been observed. For example, the current upper limits on the branching ratios for $\mu^-\rightarrow e^-\gamma$ and $\mu^-\rightarrow e^-e^-e^+$ are about 10^{-11} and 10^{-12}, respectively.[1] Experiment thus strongly supports the MSM prediction of exact family lepton-number conservation.

Nevertheless, it is widely believed that L_e, L_μ, and L_τ are not exactly conserved quantum numbers. A great amount of work has been done on extensions of the MSM which feature right-handed neutrinos, nonzero neutrino masses, and thus, in general, explicit breaking of family lepton-number symmetry. At present these theories receive only indirect experimental support from experiments indicating a solar-neutrino deficit and perhaps from the dark-matter problem. In this paper we explore the heterodox view that family lepton-number invariance may be a fundamental symmetry of nature, and that certain linear combinations may, in fact, be gauged.

It is well known that the MSM does not allow ordinary lepton-number symmetry generated by $L=L_e+L_\mu+L_\tau$ to be gauged, due to nonzero anomalies. Furthermore, no linear combination of L with B is anomaly free, where B is the generator of the other inevitable global symmetry in the MSM, namely baryon number.

It is easy to see, however, that the three symmetries generated by

$$L_1=L_e-L_\mu,\ L_2=L_e-L_\tau,\ \text{and}\ L_3=L_\mu-L_\tau \qquad (1)$$

are anomaly free in the three-generation MSM and thus may be gauged.[2] No two of these can be gauged simultaneously, though, because $L_i^2L_j$ ($i,j=1,2,3$ and $i\neq j$) anomalies are necessarily nonzero. To derive this result one considers the arbitrary linear combination $X=\alpha L_e+\beta L_\mu+\gamma L_\tau$ and calculates the criteria for the vanishing of the nontrivial anomalies $[SU(2)_L]^2U(1)_X$, $[U(1)_Y]^2U(1)_X$, and $[U(1)_X]^3$. One obtains $\alpha+\beta+\gamma=0$, $\alpha+\beta+\gamma=0$, and $\alpha^3+\beta^3+\gamma^3=0$, respectively. The only solutions to these equations are proportional to the results of Eq. (1). (Note that $[U(1)_X]^2U(1)_Y$ and $[SU(3)_c]^2\times U(1)_X$ anomalies are zero for all values of α, β, and γ.)

We thus arrive at three different theories defined by the gauge groups $G_{MSM}\otimes U(1)_{L_{1,2,3}}$. The major phenomenological consequence of these extensions is a second neutral gauge boson (Z'_1, Z'_2, or Z'_3).

It is important to appreciate that these Z' bosons can exist without the necessity for any fermions beyond the MSM with three generations. Other Z' models require exotic fermions. For instance, $U(1)_{B-L}$ may be gauged if right-handed neutrinos are added to the MSM.[3] There has also been great interest in Z' particles appearing in a variety of E_6 superstring-inspired theories.[4,5] These Z' bosons are possible only if the exotic particles in the 27-dimensional representation of E_6 exist in nature to cancel gauge anomalies. By comparison, the three models studied in this paper are extraordinarily frugal with regard to fermionic degrees of freedom.

We wish to emphasize that our motivation in studying the three theories defined above is one of minimality. These models represent the simplest possible extensions of the MSM which feature a second flavor-conserving Z boson. In contrast, the Z' bosons contained in E_6 theories are studied because they may provide a low-energy experimental signature for an underlying grand-unified theory (GUT). We are not concerned at this stage whether or not our models can be embedded in a GUT theory. It is important to study sensible extensions of the MSM which may be experimentally tested with currently existing and future accelerators, independently of speculations about physics at remote energy scales. Because we do not assume an underlying GUT model, there are no *a priori* restrictions on the values of the coupling constants.

If the coupling constant $g'_{1,2}$ of $U(1)_{L_{1,2}}$ is tiny, then it is possible that $Z'_{1,2}$ is a massless particle. Experiments on repulsion between ordinary matter yield the very stringent upper bound $g'_{1,2}<10^{-24}$.[6] A massless Z'_3 particle is less severely constrained since it only couples to second- and third-generation leptons. However, it contributes to the anomalous magnetic moment of the muon via a Schwinger-like diagram. By requiring this contribution to be less than the experimental uncertainty we obtain the upper bound $g_3' < 10^{-5}$.

It is perhaps more likely that the $U(1)_{L_i}$ local symmetry is spontaneously broken, and the Z_i' boson becomes massive via the Higgs mechanism. This is easily achieved by introducing a Higgs scalar field S_i which is neutral under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ but not under local $U(1)_{L_i}$. A nonzero vacuum expectation value for S_i then breaks local $U(1)_{L_i}$ and generates a mass for Z_i' given by $M_{Z_i'} = g_i' \langle S_i \rangle$. It is important to realize the $\langle S_i \rangle \neq 0$ breaks *local* $U(1)_{L_i}$ (which acts on leptons and S_i) down to the usual *global* symmetry $U(1)_{L_i}$ (which acts only on leptons). Thus family lepton-number conservation remains an exact principle even in the presence of massive Z_i' bosons. Even though $U(1)_{L_i}$ is a horizontal-like symmetry, its gauge particles are flavor conserving since the L_i eigenstate basis is the same as the mass-eigenstate basis. It is also important to note that the symmetry-breaking mechanism described above does *not* induce any mixing between Z_i' and the ordinary Z boson. Thus the high-precision measurements at the CERN e^+e^- collider LEP and the SLAC Linear Collider (SLC) of the Z-boson mass and width will not directly constrain Z_i' physics.[7]

We now turn to accelerator experiments on leptons in order to constrain $g_{1,2}'$ and $M_{Z_{1,2}'}$. The first group of experiments examines $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$ scattering, and extracts measurements of forward-backward asymmetries and cross sections relative to QED.

The relevant interaction Lagrangians are those for photon, ordinary Z, and $Z_{1,2}'$ coupling to fermions. They are

$$\begin{aligned}
L_A &= eA_\mu(\bar{e}\gamma_\mu e + \bar{\mu}\gamma_\mu\mu + \bar{\tau}\gamma_\mu\tau)\,,\\
L_Z &= \left(\frac{g_2}{\sqrt{1-x}}\right) Z_\mu[(x-\tfrac{1}{2})\bar{e}_L\gamma_\mu e_L + x\bar{e}_R\gamma_\mu e_R \\
&\quad + (x-\tfrac{1}{2})\bar{\mu}_L\gamma_\mu\mu_L x\bar{\mu}_R\gamma_\mu\mu_R \\
&\quad + (x-\tfrac{1}{2})\bar{\tau}_L\gamma_\mu\tau_L + x\bar{\tau}_R\gamma_\mu\tau_R]\,, \qquad (2)\\
L_{Z_1'} &= g_1' Z_{1\mu}'(\bar{e}\gamma_\mu e - \bar{\mu}\gamma_\mu\mu)\,,\\
L_{Z_2'} &= g_2' Z_{2\mu}'(\bar{e}\gamma_\mu e - \bar{\tau}\gamma_\mu\tau)\,,
\end{aligned}$$

where $x \equiv \sin^2\theta_W$ and g_2 is the $SU(2)_L$ coupling constant. We will from now on only explicitly give formulas for the $U(1)_{L_1}$ theory. Those for the $U(1)_{L_2}$ theory are trivially obtained by substituting τ for μ.

The forward-backward asymmetry A_{FB} for $e^+e^- \to \mu^+\mu^-$ (neglecting the muon mass) is

$$A_{FB} = \int_0^{\pi/2} \frac{d\sigma(\theta) - d\sigma(\pi-\theta)}{\sigma} = \frac{3}{4}\,\frac{G_{LL}^2 + G_{RR}^2 - 2G_{LR}^2}{G_{LL}^2 + G_{RR}^2 + 2G_{LR}^2}\,, \qquad (3)$$

where

$$\begin{aligned}
G_{LL} &= \frac{e^2}{s} + \frac{g_2^2}{1-x}\,\frac{1}{s-M_Z^2}(x-\tfrac{1}{2})^2 - (g_1')^2\frac{1}{s-M_{Z_1'}^2}\,,\\
G_{RR} &= \frac{e^2}{s} + \frac{g_2^2}{1-x}\,\frac{1}{s-M_Z^2}x^2 - (g_1')^2\frac{1}{s-M_{Z_1'}^2}\,, \qquad (4)\\
G_{LR} &= \frac{e^2}{s} + \frac{g_2^2}{1-x}\,\frac{1}{s-M_Z^2}x(x-\tfrac{1}{2}) - (g_1')^2\frac{1}{s-M_{Z_1'}^2}\,,
\end{aligned}$$

at the tree level due to γ-, Z-, and Z_1'-induced s-channel processes, where s is the incident four-momentum squared. A_{FB} for τ is obtained from Eqs. (2) and (3) by putting $g_1' = 0$.

The cross sections relative to the QED contribution are given by

$$\begin{aligned}
R_l &\equiv \frac{\sigma(e^+e^- \to l^+l^-)}{\sigma_{QED}(e^+e^- \to l^+l^-)}\\
&= \frac{s^2}{4e^4}(G_{LL}^2 + G_{RR}^2 + 2G_{LR}^2) \quad (l = \mu,\tau)\,. \qquad (5)
\end{aligned}$$

The second group of experiments measure neutrino-electron scattering. Data exist for the processes (i) $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$, (ii) $\nu_\mu e \to \nu_\mu e$, (iii) $\bar{\nu}_e e \to \bar{\nu}_e e$, and (iv) $\nu_e e \to \nu_e e$. The total cross sections in the $U(1)_{L_1}$ model using the Fermi approximation are

$$\begin{aligned}
\sigma(\text{i}) &= \frac{s}{8\pi}\{\tfrac{1}{3}[2\sqrt{2}G_F(x-\tfrac{1}{2}) - \xi]^2 + [2\sqrt{2}G_F x - \xi]^2\}\,,\\
\sigma(\text{ii}) &= \frac{s}{8\pi}\{[2\sqrt{2}G_F(x-\tfrac{1}{2}) - \xi]^2 + \tfrac{1}{3}[2\sqrt{2}G_F x - \xi]^2\}\,,\\
\sigma(\text{iii}) &= \frac{s}{8\pi}\{\tfrac{1}{3}[2\sqrt{2}G_F(x+\tfrac{1}{2}) + \xi]^2 + [2\sqrt{2}G_F x + \xi]^2\}\,,\\
\sigma(\text{iv}) &= \frac{s}{8\pi}\{[2\sqrt{2}G_F(x+\tfrac{1}{2}) + \xi]^2 + \tfrac{1}{3}[2\sqrt{2}G_F x + \xi]^2\}\,,
\end{aligned} \qquad (6)$$

where G_F is the Fermi constant and $\xi \equiv (g_1'/M_{Z_1'})^2$.

A χ^2 fit in the variables $r_{1,2} \equiv (g_{1,2}'/g_2)^2$ and $M_{Z_{1,2}'}$ was performed using data for these processes obtained from the summary by Amaldi *et al.*,[8] the AMY and TOPAZ Collaborations at KEK TRISTAN (Ref. 9), and recent neutrino-electron experiments reported in Ref. 10. The results and discussion are as follows.

L_1 Model. The best fit in this model yields $r_1 = 0$. This means that Z_1' exchange cannot be used to improve agreement between theory and experiment. Of more interest is the lower bound for $M_{Z_1'}$ as a function of r_1. Representative results at 90% confidence level are

$$\begin{aligned}
M_{Z_1'} &> 150\ \text{GeV} \quad \text{for } g_1' \cong 0.1 g_2\,,\\
M_{Z_1'} &> 70\ \text{GeV} \quad \text{for } g_1' \cong 0.03 g_2\,.
\end{aligned} \qquad (7)$$

The results are neither sensitive to the precise value chosen for $\sin^2\theta_W$ nor to radiative correction effects.

L_2 Model. This model only has nonstandard contributions to $e^+e^- \to \tau^+\tau^-$. In this case, Z_2' exchange improves agreement between theory and experiment, yielding a best fit for

$$\begin{aligned}
&g_2' = (3.5\text{–}4.0)\times 10^{-2} g_2 \ (\text{for } x = 0.22\text{–}0.23)\\
&\text{and } M_{Z_2'} = 60\ \text{GeV}\,.
\end{aligned} \qquad (8)$$

This result is similar to that obtained in an analysis of

TRISTAN data by Hagiwara *et al.*[5] who showed that an improved fit was obtained when a Z' originating from an E_6 theory was included. The statistical significance of this result should not be overestimated; a best fit using the MSM still yields an acceptable value for χ^2. Our result can be understood by examining Eqs. (4) and (5) which show that Z_2' *s*-channel effects raise the magnitude of the cross section. (Z_1' effects are of the wrong sign relative to the data to yield a better fit for R_μ.) Experimental data indeed yield a slightly higher value for the cross section in the 45–62 GeV energy range than predicted by the MSM (see, for example, Ref. 11). We also find that χ^2 in this model does not vary strongly with r_2 and $M_{Z_2'}$, so the minimum at the best-fit values is not very deep. For this reason there is essentially no upper or lower bound for $M_{Z_2'}$ at 90% confidence level.

The fact that both types of Z' bosons can have masses in the 60–200 GeV range means that they could possibly be produced in current e^+e^- machines or at LEP2. One may be tempted to conclude that if these bosons have mass less than 63 GeV, then they would have been produced at TRISTAN unless their coupling constants were really very small.

Of perhaps more interest is the intriguing possibility that the mass could lie in the "window" between the TRISTAN lower bound of about 63 GeV and the LEP upper bound of about 87 GeV. The relevant quantities are the width of the Z' particle and the maximum value of its production cross section.

For the L_1 model the coupling constant for the mass range defined by the window is at most about $0.03g_2$. For $M_{Z_1'}=75$ GeV this yields $\Gamma_{tot}(Z_1')<0.003$ GeV, which is a very small width. For the L_2 model and for $M_{Z_2'}=75$ GeV, the 90% confidence level upper bound on g_2' is about $0.3g_2$. This gives $\Gamma_{tot}(Z_2')<0.25$ GeV with the best-fit value for g_2' yielding $\Gamma_{tot}(Z_2')\cong 0.01$ GeV. These numbers again indicate that the Z_2' resonance, if it exists, is rather narrow. Consequently, it is likely that the tail of this resonance would have negligible effects at TRISTAN energies or near the standard Z resonance. In order to discover such a narrow resonance the energy window would need to be traversed in very small steps.

If produced, these Z' particles would be detected via their decays to *muon* or τ pairs, depending on the model. In either case, we can get a feeling for how observable the resonance would be by calculating the ratio of the total cross sections integrated with respect to $\sqrt{s}$ for $e^+e^- \to l^+l^-$ ($l=\mu,\tau$) going via a real Z' particle and a real standard Z particle. We estimate that for Z' masses of 75 GeV this ratio is <0.3 at 90% confidence level for model 1, while for model 2 the best-fit parameters yield about 0.4. Thus we would expect a Z_2' in the window to be a narrow resonance of comparable area to the standard Z. A Z_1' resonance would certainly be very narrow, but it would in general yield a much weaker signal.

We end our analysis with the comment that since the widths of these particles can be so small, there is the bizarre possibility that TRISTAN may have actually "stepped over" such a resonance, for the case where the masses are less than 63 GeV.

Finally, Z_3' interactions are constrained only via their one-loop contribution to $(g-2)_\mu$. The bound is $M_{Z_3'} \gtrsim 100g_3'$ GeV. This bound is significantly weaker than those from the tree-level processes considered above for the two other types of Z' bosons.

In conclusion, we have shown that present bounds on the interactions of Z' bosons coupling to $L_{1,2}$ do not preclude their playing an important role in e^+e^- accelerator physics in the near future. In particular, we have demonstrated that they may be relevant for energies in the TRISTAN-LEP window of 63–87 GeV. It is quite possible for a Z_2' boson to appear as a rather narrow resonance in this region with a cross section integrated with respect to $\sqrt{s}$ comparable to that of the standard Z resonance.

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[1]Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988).

[2]We thank R. Foot for pointing this out to us. The implications for charge quantization of these symmetries are explored in R. Foot, Wisconsin University, Madison Report No. MAD/TH/90-14, 1990 (unpublished).

[3]X.-G. He, G. C. Joshi, and R. R. Volkas, Phys. Lett. B **240**, 441 (1990); S. L. Glashow and U. Sarid, Phys. Rev. Lett. **64**, 725 (1990); F. del Aguila, J. M. Moreno, and M. Quirós, CERN Report No. CERN-TH.5646/90, 1990 (unpublished).

[4]G. Altarelli *et al.*, Mod. Phys. Lett. A **5**, 495 (1990); Phys. Lett. B **245**, 669 (1990); Nucl. Phys. **B342**, 15 (1990); M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B **236**, 360 (1990); Phys. Rev. D **41**, 2355 (1990); S. L. Glashow and U. Sarid, Phys. Lett. B **246**, 188 (1990); for earlier references, see J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989).

[5]K. Hagiwara, R. Najima, M. Sukuda, and N. Terunuma, Phys. Rev. D **41**, 815 (1990).

[6]L. B. Okun, *Leptons and Quarks* (North-Holland, Amsterdam, 1982), Sect. 19.4.

[7]Mixing between Z_i' and the standard Z may be introduced by extending the Higgs sector (e.g., Higgs triplets which couple to $\bar{\nu}_{eL}^c \nu_{eL}$, etc., may be used).

[8]U. Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987).

[9]AMY Collaboration, A. Bacala *et al.*, Phys. Lett. B **218**, 112 (1989); TOPAZ Collaboration, I. Adachi *et al.*, *ibid.* **208**, 319 (1988).

[10]J. Panman, in *Proceedings of the XIVth International Symposium on Lepton and Photon Interactions*, Stanford, California, 1989, edited by M. Riordan (World Scientific, Singapore, 1990); contributed papers to the above conference: K. Abe *et al.* (Paper No. 047); CHARM-II Collaboration, D. Geiregat *et al.* (Paper No. 149); G. S. Vidyakin *et al.* (Paper No. 292).

[11]A. Maki, in *Proceedings of the XIVth International Symposium on Lepton and Photon Interactions* (Ref. 10).