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Left-Right Symmetry and the Mass Scale of a Possible Right-Handed Weak Boson*

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ABSTRACT

Some features of the $SU(2)_L \times SU(2)_R \times U(1)$ gauge theory of the electroweak interactions are discussed. It is argued that a Charge-Conjugation Conserving Lagrangian provides the most reasonable version of the theory, leading to phenomenological consequences which differ from those of the so-called "manifest left-right symmetry" scheme. New constraints on the parameters of the theory are presented. Several lines of reasoning lead us to the conclusion that the most likely value for the mass of the right-handed charged W-boson is around 10 TeV (within a factor two).

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1. INTRODUCTION

The standard $SU(2)\times U(1)$ gauge theory[1] for electroweak interactions is presently consistent with all available experiments, including the recent discoveries of the W and Z bosons.[2] In the standard theory, the gauge symmetry is broken spontaneously, while discrete symmetries such as parity and charge conjugation are broken explicitly.

It is possible to construct "left-right symmetric" (LRS) extensions of the standard model, in such a way that parity is also broken spontaneously.[3] The Lagrangian of the simplest LRS model is invariant under an $SU(2)_L\times SU(2)_R\times U(1)$ gauge symmetry, with the $SU(2)_L$ and $SU(2)_R$ coupling constants g_L and g_R being equal. Parity is conserved in the Lagrangian and is broken spontaneously together with the gauge symmetry. The LRS theory is consistent, at present, with all experimental data, provided that some of its free parameters obey certain bounds.

In addition to its special treatment of parity violation, the LRS theory has other attractive features: (i) The U(1) factor turns out[4] to represent B-L (Baryon minus lepton number); (ii) The theory contains a simple built-in mechanism[5] for obtaining a Majorana mass for the neutrino, predicting a light left-handed neutrino and a heavy right-handed neutrino; (iii) The $SU(2)_R$ group leads to weak CP-violating effects[6] whose magnitude is related to that of the right-handed currents.

The most important undetermined parameter of the LRS model is the mass scale of the right-handed bosons. Other unknown parameters include the mixing between $W_L^{\pm}$ and $W_R^{\pm}$ and the Cabibbo-like angles for the right-handed sector of the theory.

During the past two years, many authors[7-13] have analyzed various aspects of the LRS theory, deriving bounds and constraints on its parameters. Most of these calculations were done within the framework of a specific version of the theory, in which all right-handed Cabibbo-like angles and phases are equal to the corresponding left-handed parameters. This assumption is usually referred to as "manifest left-right symmetry."[14]

In this paper we argue that the so-called "manifest LRS" model should not be considered as the most attractive or as the leading version of the LRS theory. In fact, we claim that a different variant of the theory is the most reasonable contender and that its predictions and constraints differ from those of the "manifest LRS" scheme. The variant that we recommend has one central feature: Its Lagrangian conserves not only parity, but also charge conjugation and <u>all</u> its symmetries are broken spontaneously. We refer to it as the CCC (Charge-Conjugation Conserving) version of the theory. We believe that the only motivation for considering a LRS-theory in the first place (namely: spontaneous breaking of all symmetries, not only gauge symmetries) should apply equally to parity and to charge conjugation. The Lagrangian of the so-called "manifest LRS" model conserves parity but breaks charge conjugation explicitly and is, therefore, in our opinion, an unlikely candidate for an LRS theory.

We start our discussion by defining the CCC-version of the theory. We then review some of the constraints which have recently been derived, using "manifest LRS." We show that some of these results remain valid in the CCC version, while others do not apply. We finally argue that, within the CCC model, it is likely that the order of magnitude of the mass of the right-handed charged W-boson is around 10 TeV (within a factor two).

2. THE CHARGE-CONJUGATION CONSERVING (CCC) VERSIONS OF THE LRS THEORY

The LRS-theory[3,5,6] involves seven gauge bosons, corresponding to the seven generators of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The minimal Higgs spectrum includes a complex $(1/2,1/2)_0$ field ϕ as well as $(0,1)_2$ and $(1,0)_2$ fields Δ_R and Δ_L[5]. The vacuum expectation values are:

$$\langle\Delta_L\rangle = \begin{pmatrix} 0 \\ 0 \\ v_L \end{pmatrix} \; ; \; \langle\Delta_R\rangle = \begin{pmatrix} 0 \\ 0 \\ v_R \end{pmatrix} \; ; \; \langle\varphi\rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix} \qquad (1)$$

The mass matrix for the charged vector particles is given by:

$$M^2(W^\pm) = \frac{1}{2} g^2 \begin{pmatrix} 2|U_L|^2 + |k|^2 + |k'|^2 & -2k'k^* \\ -2kk'^* & 2|U_R|^2 + |k|^2 + |k'|^2 \end{pmatrix} \quad (2)$$

The mass matrices for the up and down sectors of the quarks are given by:

$$M^U = kA + k'^* B \quad (3)$$

$$M^D = k'A + k^* B \quad (4)$$

where A and B are $n\times n$ matrices describing the Yukawa couplings of the ϕ-fields to n generations of quarks.

In order to obtain $M(W_R) \gg M(W_L)$ we must have $|U_R|^2 \gg |k|^2 + |k'|^2$ and $|U_R|^2 \gg |U_L|^2$. In order to preserve the Weinberg mass relation $M(W_L) = M(Z)\cos\theta_W$, we must have $|U_L|^2 \ll |k|^2 + |k'|^2$. We therefore must assume that U_L is negligible. The ratio k/k' is related to the amount of W_L-W_R mixing. If we define mixing parameters ξ,η such that the physical charge vector bosons are:

$$\begin{aligned} W_1 &= W_L \cos\xi + W_R e^{i\eta} \sin\xi \\ W_2 &= -W_L e^{-i\eta} \sin\xi + W_R \cos\xi \end{aligned} \quad (5)$$

we find, for small ξ:

$$|\xi| \sim 2\left|\frac{k}{k'}\right|\left[\frac{M(W_L)}{M(W_R)}\right]^2 \qquad (6)$$

Direct determinations of ξ for β-decay experiments give bounds of the order of[14] $\xi<0.06$, hopefully soon to be improved by new experiments. An indirect analysis of nonleptonic K-decays, using current algebra, PCAC and Bag model estimates yields a much stronger bound[15] $\xi<0.004$ which is, however, subject to substantial theoretical uncertainties. If we take, for instance, $\xi\sim0.01$ and $M(W_R)\sim1$ TeV, we obtain $|k/k'|\sim0.7$. Hence, very small values of the mixing parameter ξ are perfectly consistent with a not-so-small k/k' ratio. This is especially true if $M(W_R)$ is of the order of a few TeV. The limit $k/k'\to0$ is therefore phenomenologically unnecessary and theoretically dangerous, since it may lead to unwanted new symmetries.

The "manifest LRS" model <u>assumes</u> that the left-handed and right-handed Cabibbo matrices C_L and C_R are equal. This necessitates real values for k and k' and complex Yukawa couplings in the A and B matrices of equations (3),(4). However, there is no reason for k and k' to be real even in the case that we have only one ϕ Higgs multiplet. It is certainly unlikely that all k_i, k_i' values are real in the case of several ϕ_i Higgs multiplets. On the other hand, if the Lagrangian of the theory conserves charge-conjugation (i.e. the CCC-version), the Higgs couplings A and B must be real (for any number of Higgs multiplets) while the vacuum expectation values k and k' are complex. In the CCC scheme we may always choose a representation of the quark fields such that:

$$C_R = C_L^* \tag{7}$$

If we insist on the usual conventions in which the first row and the first column of the left-handed Cabibbo matrix C_L are real, we obtain (in that convention):

$$C_R = F^U C_L^* (F^D)^* \tag{8}$$

where F^U, F^D are diagonal unitary matrices:

$$F^U = \begin{pmatrix} e^{i\varphi_u} & 0 & 0 \\ 0 & e^{i\varphi_c} & 0 \\ 0 & 0 & e^{i\varphi_t} \end{pmatrix}; \quad F^D = \begin{pmatrix} e^{i\varphi_d} & 0 & 0 \\ 0 & e^{i\varphi_s} & 0 \\ 0 & 0 & e^{i\varphi_b} \end{pmatrix} \tag{9}$$

We conclude that the CCC-model contains an additional set of arbitrary phases relating the left-handed and the right-handed Cabibbo matrices. These phases are, in principle, free parameters on the same footing as the Cabibbo angles, and the Kobayashi-Maskawa phase. In the case of two generations, these relative left-right phases lead to CP-violating amplitudes,[6] which do not exist in a "manifest LRS" two-generation model.

We summarize: we have considered two versions of the LRS theory. The first is the popular "manifest LRS" model. It assumes $C_L = C_R$ and therefore contains a smaller number of parameters. It has complex Yukawa couplings and real vacuum expectation values for the Higgs fields. Its Lagrangian does not conserve charge conjugation and therefore misses the main purpose of all LRS models. The second version[6,12,13] has a C-conserving Lagrangian, real Yukawa couplings, complex vacuum expectation values and additional phase parameters relating C_L and C_R. Regardless of any phenomenological considerations, we believe that the CCC version should be preferred, since P and C conservation should be treated on the same footing. We now turn to the consequences of the CCC version of the theory.

3. K_S-K_L MASS DIFFERENCE AND THE CCC MODEL

The most powerful bound on the mass of W_R has been derived by Beall, Bander and Soni.[7] These authors considered the W_L-W_R box diagram and postulated that its contribution to the K_S-K_L mass difference is smaller than that of the standard Gaillard-Lee[16] box diagram involving two W_L-bosons. In their calculation, Beall et al. considered only two generations of quarks and assumed "manifest LRS." They obtained the bound:

$$430\left[\frac{M(W_L)}{M(W_R)}\right]^2 \leq 1 \qquad (10)$$

yielding $M(W_R) \geq 1.7$ TeV. The numerical factor of 430 is the main interesting result of this calculation, since it is the product of three factors, each of which is a priori "of order one" but turns out to obtain values between 5 and 10.

In the CCC-model (still in the case of two generations), this result is modified into:

$$430 \cos\gamma \left[\frac{M(W_L)}{M(W_R)}\right]^2 \leq 1 \tag{11}$$

where γ is an unknown relative phase between the right- and left-handed Cabibbo matrices [see Eq. (8)]. It would momentarily appear that the bound of Eq. (10) is lost, since γ can obtain any value and for a sufficiently small $\cos\gamma$, any $M(W_R)$ is acceptable. However, the same phase parameter γ is the only source of CP-violation within the same two-generation CCC-model. We therefore obtain:[13]

$$430 \sin\gamma \left[\frac{M(W_L)}{M(W_R)}\right]^2 \sim 2\sqrt{2}\,|\varepsilon| \tag{12}$$

In deriving equation (12) we have actually used two different phase conventions: In one of them $CP|K^0\rangle = -|\bar{K}^0\rangle$ while in the other $\langle(2\pi)_{I=0}|H_W|K^0\rangle$ and $\langle(2\pi)_{I=0}|H_W|\bar{K}^0\rangle$ are relatively real. It is not difficult to show that the phase difference between these two conventions is negligible.[(12)(13)]

We can now combine equations (11) and (12) to obtain the modified bound:

$$430\left[\frac{M(W_L)}{M(W_R)}\right]^2 \leq \left(1+8|\varepsilon|^2\right)^{1/2} \tag{13}$$

Since experimentally $8|\varepsilon|^2 \ll 1$, we have recovered the bound of Eq. (10) and we still find $M(W_R) \gtrsim 1.7$ TeV!

An important consequence of Eq. (12) is the following: If $M(W_R)$ is anywhere near 1.7 TeV, the phase angle γ must be smaller than 10^{-2}. We do not know of any "natural" reason for having such a small value of γ. On the other hand, if γ is "normal," e.g. $|\sin\gamma|>0.1$, we are immediately led[13] to much higher values of $M(W_R)$. We return to this point in Section 5 when we discuss CP-violation.

The bound of Beall et al.[7] depends on a variety of dynamical assumptions, and could be modified if we include intermediate-state corrections or use another model to calculate the matrix element, or consider QCD corrections to the amplitude, etc. (still in the case of two-generations). We believe that all of these corrections are not likely to change the numerical factor of 430 by more than a factor 3. On the other hand, the contribution of the W_L-W_R box diagram is actually likely to be smaller than the Gaillard-Lee term, rather than equal to it. We may therefore safely conclude that, in the case of two generations, a definite lower bound on $M(W_R)$ is indeed found somewhere in the 1-2 TeV range.

The inclusion of a third generation of quarks leads to several important effects. First, we must now consider the t-quark contributions to the W_L-W_L[16] and the W_L-W_R[7] box diagrams. We must also consider contributions of "unphysical" scalars which are suppressed by factors of order $m_q/M(W_R)$. The size of these contributions depend on m_t and on the various Cabibbo angles. If we assume that the t-quark contributions to ΔM, by themselves, are smaller than the Gaillard-Lee term, we obtain bounds[17] on $\sin\theta_2$ but the bound[7] on $M(W_R)$ is not seriously affected. We believe that this is a perfectly reasonable assumption. However, if we allow for substantial cancellations between the t-quark terms and other W_R-contributions, we may get a weaker bound[8] on $M(W_R)$ for sufficiently large values of m_t. The recent determination of the b-quark lifetime[18] now leads to severe bounds on θ_2 and θ_3, implying that all t-quark contributions to ΔM are actually quite small.

A second important effect which is introduced by the third generation of quarks is the usual Kobayashi-Maskawa (KM) contribution to CP violation. Our Eq. (12) is not valid anymore and ε may have, in addition, pure left-handed contributions proportional to $\sin\delta$, where δ is the usual KM-phase. We cannot predict the relative size of the two contributions to ε. However, it is probably safe to assume that each one of these contributions, by itself, is not much larger than the experimental value of ε. (In other words--we simply assume that we do not have a very precise accidental cancellation of two large numbers.) In that case, Eq. (12) can be replaced by an inequality and the bound $M(W_R) \geq 1.7$ TeV remains valid.

In the next section we discuss the contributions of the Higgs fields to the K_S-K_L mass difference. However, at the present stage we conclude that $M(W_R)$ is almost certainly above 1 TeV, and for "sensible" values of the phase parameter γ, we probably have a substantially heavier W_R.

4. HIGGS COUPLINGS AND THE K_S-K_L MASS DIFFERENCE

An important contribution to the K_S-K_L mass difference is due to the neutral Higgs bosons. The LRS theory must contain at least four neutral complex Higgs fields--Δ_L^0, Δ_R^0, and the two neutral components of ϕ. Of these, two (real) fields are "absorbed" by Z and Z', some of the others do not couple to fermions and at least two real physical neutral Higgs fields must couple to $\bar{s}d$ and $\bar{d}s$, yielding a contribution[10] which is proportional to m_H^{-2}, where m_H is the mass of the relevant Higgs particle. In order that the Higgs contribution be smaller than the standard Gaillard-Lee term, m_H should be at least somewhere around 5-10 TeV. The natural value of m_H is around $M(W_R)$ or, at most, slightly above it. Hence, if $M(W_R)$ is larger than a few TeV, the Higgs contribution need not pose any serious problems. This is probably the most likely situation, and it leads, again, to W_R-values above a few TeV.[19]

An alternative possibility is a more-or-less accidental vanishing[10] of the Higgs couplings which induce the relevant contribution to ΔM. In the manifest LRS model, the condition for a vanishing Higgs contribution is:[11]

$$\sum_i m_i (C_L)_{si} (C_L)_{di} \sim 0 \qquad (14)$$

where C_L is the left-handed Cabibbo matrix and $i=u,c,t$. In the CCC-model, the relevant condition is:[19]

$$\sum_i m_i e^{-2i\varphi_i} (C_L)_{si} (C_L)_{di} \sim 0 \qquad (15)$$

where ϕ_i $(i=u,c,t)$ are the phases defined in Eq. (9). Neglecting terms of order m_u/m_c and m_u/m_t and assuming $\cos\theta_j \sim 1$ for $j=1,2,3$ we obtain in the CCC-model:

$$m_c e^{2i(\varphi_t-\varphi_c)} + m_t s_2 (s_2 + s_3 e^{-i\delta}) \sim 0 \qquad (16)$$

where $s_2 \equiv \sin\theta_2$; $s_3 \equiv \sin\theta_3$ and δ is the KM angle. We assume $-180° \le (\phi_t - \phi_c) \le 180°$. In the "manifest LRS" model we obtain a similar equation, except that we must set $\phi_t = \phi_c = 0$:

$$m_c + m_t s_2 (s_2 + s_3 e^{-i\delta}) \sim 0 \qquad (17)$$

Assuming a "manifest LRS" model, Gilman and Reno have recently showed[11] that the known experimental limit on the branching ratio between the weak transitions $b \to ue\nu$ and $b \to ce\nu$ forces the parameters θ_2, θ_3 and δ into a relationship which contradicts Eq. (17). They conclude that the "manifest LRS" model does not allow a small Higgs coupling. We will now show that this conclusion does not hold in the CCC-model.

Following the analysis of Gilman and Reno[11] we define:

$$r = \frac{\Gamma(b \to u e \nu)}{\Gamma(b \to c e \nu)} \tag{18}$$

we obtain:

$$x^2 + 2x\cos\delta - K = 0 \tag{19}$$

or:

$$(x + \cos\delta)^2 = K + \cos\delta \tag{20}$$

where

$$x \equiv \frac{s_2}{s_3} > 0 \tag{21}$$

$$K = \frac{0.12}{r} - 1 \tag{22}$$

The present experimental limit[20] is $r<0.05$, hence $K>1.4$. Consequently:

$$|x + \cos\delta| > 1.2 \tag{23}$$

Since $x>0$, we must have $x+\cos\delta>-1$. Equation (23) then implies that $(x+\cos\delta)$ is positive. Equation (16) can be rewritten as:

$$m_c \cos 2(\varphi_t - \varphi_c) = -m_t s_2 s_3 (x + \cos\delta) \tag{24}$$

$$m_c \sin 2(\varphi_t - \varphi_c) = m_t s_2 s_3 \sin\delta \tag{25}$$

Since $(x+\cos\delta)$ is positive we must have a negative $\cos 2(\phi_t-\phi_c)$, hence $45^\circ<|\phi_t-\phi_c|<135^\circ$. Dividing (24) by (25) we obtain:

$$-\cot 2(\varphi_t-\varphi_c) = \frac{x+\cos\delta}{\sin\delta} \tag{26}$$

Hence:

$$|\cot 2(\varphi_t-\varphi_c)| = \frac{|x+\cos\delta|}{|\sin\delta|} > 1.2 \tag{27}$$

or:

$$70^\circ < |\varphi_t-\varphi_c| < 110^\circ \tag{28}$$

Any improvement in the experimental bound on r (as defined in Eq. (18) would push $|\phi_t-\phi_c|$ further towards 90° (e.g. for $r<0.02$ we have $78^\circ<|\phi_t-\phi_c|<102^\circ$, etc.).

Equation (24) now leads to aother useful bound:

$$s_2 s_3 = \frac{m_c}{m_t}\cdot\frac{|\cos 2(\varphi_t-\varphi_c)|}{x+\cos\delta} \lesssim 0.8\,\frac{m_c}{m_t} \tag{29}$$

The negative result of Gilman and Reno for the case of "manifest LRS" can be directly obtained from Eq. (24) by setting $\phi_t=\phi_c=0$ and observing that the two sides of the equation must have opposite signs. Our analysis shows that in the CCC version, $|\phi_t-\phi_c|$ must actually be near 90°, in order to allow a small Higgs coupling to $\bar{s}d$ and $\bar{d}s$.

We must emphasize that the above analysis, as well as the conclusion of Gilman and Reno, are relevant only if $M_H<5$ TeV and if the Higgs contribution is suppressed by its small coupling rather than by a large Higgs mass. The recent measurement of the b-quark lifetime[18] actually indicates that s_2 and s_3 may be too small for the required suppression of the Higgs coupling.

Our conclusion is the following: the most natural suppression of the neutral Higgs contribution to the K_S-K_L mass difference, in any LRS theory is to assume $m_H \gtrsim 5$ TeV, leading to $M(W_R)>$few TeV. A somewhat unnatural, but not completely excluded, possibility is to have a much smaller value of m_H and to have at least a partial cancellation of the terms in the Higgs coupling. This is possible in the CCC-version, leading to constraints on the phase parameters. It is not possible in the "manifest LRS" version.[11]

5. CP-VIOLATION IN THE CCC MODEL

We have already remarked that in the CCC-version of the LRS theory, there are two mechanisms for CP-violation. One is due to the relative phases between the left-handed and right-handed Cabibbo matrices [Eq. (12)] and the other is the usual KM mechanism leading to a contribution of the form:[21]

$$|\varepsilon| = s_2 s_3 \sin\delta \cdot f\left(\frac{m_t}{m_c}, \theta_2\right) \tag{30}$$

where $f(m_t/m_c, \theta_2)$ is a known function.

As long as the two CP-violating mechanisms are present, we cannot make definite predictions concerning their relative importance. However, two comments are in order:

(i) In the minimal standard model, sufficiently small values of s_2 and s_3 lead to lower bounds on the t-quark mass. For instance, if the b-quark lifetime is sufficiently long, the parameters s_2 and s_3 must be small, leading to a non-trivial lower limit on the value of $f(m_t/m_c, \theta_2)$ in Eq. (30). For large m_t and fixed θ_2, f is an increasing function of m_t. Hence, we get a lower limit[22] on m_t. For the new value of the b-quark limetime, m_t values around 40 GeV or less may actually be excluded by the standard model.[22] All of this argumentation becomes invalid in the CCC version of the LRS theory, since there Eq. (12) may be responsible for a large or even a dominant contribution to ε. In fact, we may turn the argument around and state that if the b-quark lifetime[18] is around 10^{-12} sec (or more) and <u>if the t-quark mass is around 40 GeV (or less) the LRS theory becomes a likely candidate for explaining the remaining contribution to CP-violation.</u>

(ii) If the contribution of Eq. (30) to ε is not dominant, Eq. (12) may turn out to be approximately correct (say, within a factor of two). In that case, we obtain an <u>upper bound</u> on $M(W_R)$:

$$\left[\frac{M(W_R)}{M(W_L)}\right]^2 \leq \frac{430}{2\sqrt{2}|\varepsilon|} \qquad (31)$$

or:

$$M(W_R) \leq 21 \text{ TeV} \qquad (32)$$

If only 50% of ε come from Eq. (12), the bound rises to 30 TeV, etc. At the same time, we still have the ambiguities in determining the numerical factor 430, and those are likely to push the bound (32) downward.

Combining this latest bound with the bound (10) of Beall et al., we obtain:

$$1.7 \text{ TeV} \leq M(W_R) \leq 21 \text{ TeV} \qquad (33)$$

Moreover, as we remarked earlier, values of $M(W_R)$ near the lowest part of the allowed range require extremely small unnatural values of the relative right-left phase γ. For "reasonable" values such as $|\sin\gamma| > 0.1$ we obtain:

$$7 \text{ TeV} \leq M(W_R) \leq 21 \text{ TeV} \qquad (34)$$

It is remarkable that this range agrees well with the required mass of the neutral Higgs particle discussed in Section 4. In the absence of a good reason for a very small value of γ we therefore conclude that $M(W_R)$ should be of the general order of magnitude of 10 TeV (within a factor of two).

We emphasize that all the conclusions in Eqs. (31)-(34) depend crucially on the assumption that the KM-mechanism cannot account for the observed value of ε and that a substantial contribution from the relative left-right phases is needed.

6. SUMMARY AND DISCUSSION

Aside from a variety of technical remarks and bounds, we have tried to emphasize here two main points:

(A) Within the framework of the LRS theory, the most reasonable variant of the theory is the Charge-Conjugation Conserving (CCC) scheme. Its advantages are mostly theoretical, but it leads to different phenomenological consequences, especially as a result of additional phase parameters. At the same time, its predictive power is not very different from that of the C-violating "manifest LRS" model.

(B) A variety of plausibility arguments led us to the conclusion that the most likely value for the mass of the W_R-boson in the CCC model is around 10 TeV (within a factor of 2). We do not have rigorous bounds leading us to this range, but we are relying on the following points: (i) The lower bound of Beall et al.[7] is 1.7 TeV; (ii) If the relative left-right phases contribute significantly to ε, we have an upper limit of the order of 20 TeV; (iii) If γ is not extremely small, the lower bound rises significantly;

(iv) The neutral Higgs contribution to the K_S-K_L mass difference is naturally small if $m_H > 5$ TeV, leading to similar values of $M(W_R)$.

We also note that in the case of the simplest Higgs sector, the LRS model yields:[5,23]

$$\left[\frac{M(W_R)}{M(Z')}\right]^2 = \frac{\cos 2\theta_W}{2\cos^2\theta_W} = 0.35 \tag{35}$$

Hence:

$$M(Z') \sim 1.7\, M(W_R) \tag{36}$$

The possibility of finding W_R and Z' at energies as high as 10-20 TeV is, of course, somewhat disappointing from an experimental point of view. It also implies that the vacuum expectation values of Eq. (1) obey:

$$\frac{|k|^2 + |k'|^2}{|v_R|^2} \sim O(10^{-4}) \tag{37}$$

In the case of a dynamical symmetry breaking, this implies that different dynamical mechanisms must be at work here, either as a result of different gauge groups or, more likely, as a result of very different types of condensates.

If $M(W_R)$ is around 10 TeV, W_L-W_R mixing is guaranteed to be negligible regardless of the ratio k/k' [see Eq. (6)] and will not be observable in low-energy experiments; the W_R contribution to the K_S-K_L mass difference is very small; the contributions to CP-violation are likely to be substantial and may be the first indirect evidence for LRS. However, the first <u>direct</u> evidence for right-handed currents will have to await experiments in the TeV range and a discovery of W_R and Z' will require lepton colliders with energies around 20 TeV or hadron colliders with 50 TeV or more.

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[19]After completing this work we have learned from F.J. Gilman about a preprint by G. Ecker, W. Grimus and H. Neufeld, CERN-TH-3551, in which similar conclusions have been reached.

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