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RESTRICTIONS FROM THE NEUTRAL K AND B MESON SYSTEMS ON LEFT-RIGHT SYMMETRIC GAUGE THEORIES

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ABSTRACT

We investigate constraints on flavor-changing neutral Higgs boson masses and couplings in left-right symmetric gauge theories which arise from the neutral K and B meson systems. The mass of such bosons must be in the multi-TeV region to avoid unacceptably large $K^0 - \bar{K}^0$ or $B^0 - \bar{B}^0$ transition amplitudes.*

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1. Introduction

Left-right symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ have received considerable attention as simple extensions of the standard Glashow-Weinberg-Salam model.[1] The attractions are many. The unbroken Lagrangian is invariant under the gauge group with the coupling constants g_R and g_L equal. It has been shown that an asymmetric solution to the Higgs potential is possible,[2] so parity symmetry may be broken spontaneously. By appropriate choices of some of the free parameters of the left-right symmetric (LRS) theories, their predictions for low energy phenomena can be made to be similar to those of the standard model and consistent with experiments. However, distinct from the standard model, LRS models predict new physics at a higher energy scale, e.g., the restoration of parity symmetry, the presence of the $SU(2)_R$ gauge particles $W_R^{\pm}$ and Z_R^0, physical charged and neutral Higgs bosons and, in some models, heavy Majorana neutrinos.[3] The free parameters of LRS theories include quark and lepton masses, quark and lepton mixing angles for both left- and right-handed charged currents, masses of gauge bosons and physical Higgs particles, and mixing angles between mass and gauge eigenstates of the gauge bosons.

In particular, phenomenological constraints on the masses of the gauge bosons have been studied by many authors. If right-handed neutrinos are light, limits on deviations from V-A currents in muon decay[4] put a lower bound on the mass of the charged gauge boson associated with $SU(2)_R$: $M_R > 380$ GeV. An assumption about the mass of right-handed neutrinos can be avoided by studying nonleptonic kaon decays. The result[5] is an approximate lower bound of $M_R \gtrsim 300$ GeV; however, the theoretical analysis of such decays has its own uncertainties.

The $K^0 - \bar{K}^0$ system also turns out to be quite sensitive to the mass of $W_R^{\pm}$. Beall, Bander and Soni[6] considered the box diagram contributions to the $K_S^0 - K_L^0$ mass difference arising from the presence of $W_R^{\pm}$ as well as $W_L^{\pm}$ in a so-called manifest LRS theory characterized by Hermitian Yukawa couplings and real vacuum expectation values of the Higgs fields. In the limit where the top quark contribution is small, they found $M_R \gtrsim 1.6$ TeV if there is to be an acceptable value of the $K_S^0 - K_L^0$ mass difference. Several other authors[7,8] have reexamined and extended their analysis to include the contributions from the t quark and Higgs bosons. In particular, Mohapatra *et al.*[8] included the contributions of neutral Higgs bosons. Because the theory has several neutral complex Higgs fields which contribute to the quark mass matrices, there generally are flavor-changing neutral Higgs couplings which result in tree level Higgs contributions to the $K_S^0 - K_L^0$ mass difference. In the manifest LRS theory, Mohapatra *et al.*[8] found that including the neutral Higgs contribution with particular values of the weak mixing angles allowed M_R to be as low as 200 GeV, while still satisfying the constraint of having acceptable values of the $K_S^0 - K_L^0$ mass difference.

In a previous short paper[9] we showed that these weak mixing angles are just those so as to make the $s \leftrightarrow d$ quark flavor-changing neutral Higgs coupling almost vanish, but that the resultant domain of angles contradicted information on $(b \to u)/(b \to c)$. To prevent disastrously large contributions to $\Delta M_K = M_{K_S} - M_{K_L}$ these Higgs masses must be raised to be of order 10 TeV.

In this paper we expand on this subject. We investigate the constraints on neutral Higgs flavor-changing couplings and masses due to the neutral K and B meson systems in LRS theories. In particular we find that recent information on the b lifetime independently rules out the domain of Mohapatra *et al.*[8] unless

$m_t \gtrsim 250$ GeV. More generally we look at the constraints that suppression of neutral Higgs contributions imposes on both manifest and pseudo-manifest (also called charge conjugation conserving theories[10–12]) LRS theories. With $m_t \lesssim$ 250 GeV the b lifetime rules out making the $s \leftrightarrow d$ neutral Higgs' flavor-changing coupling vanish in either class of theories. To avoid an unacceptable contribution to ΔM_K the Higgs mass must be $\gtrsim 8$ TeV. Furthermore, in either class of theories the $b \leftrightarrow d$ flavor-changing Higgs coupling cannot be made small, and therefore the constraint of lack of complete mixing in the neutral B meson system can only be satisfied by raising the Higgs mass. For $m_t \gtrsim 250$ GeV we find that the Higgs with flavor-changing couplings must have mass $M_H \gtrsim 2$ TeV.

In Section 2 we will discuss the general LRS theory, paying particular attention to the neutral Higgs interaction terms. An analysis of the neutral Higgs contribution to ΔM_K and the resulting constraints are presented in Section 3. Section 4 centers on a similar discussion for the neutral B meson system. We offer our conclusions in Section 5.

2. Left-Right Symmetric Models

In this section we will describe some features of LRS models relevant to our discussion of the neutral K and B meson systems. More complete discussions may be found in the literature.[2,8,10–12] We will generally follow the notation of Mohapatra *et al.*[8]

For a left-right symmetric Lagrangian with gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ the left-handed fermions are assigned to the representation (1/2, 0, n) and the right-handed fermions to (0, 1/2, n). The $B-L$ quantum number n has the value 1/3 for quarks and -1 for leptons.

In such a theory, the minimal Higgs sector which will both break the parity symmetry as well as give the fermions and gauge bosons their masses involves[2,13] the fields Δ_L, Δ_R and Φ (plus its charge conjugate $\tilde{\Phi} = \tau_2 \Phi^* \tau_2$). These Higgs multiplets are chosen to transform under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ as (1, 0, 2), (0, 1, 2), and (1/2, 1/2, 0) respectively. The complex fields

$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \tag{1a}$$

and

$$\vec{\tau} \cdot \vec{\Delta}_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix} \tag{1b}$$

have vacuum expectation values

$$\langle\Phi\rangle = \begin{pmatrix} k e^{i\beta_1} & 0 \\ 0 & k' e^{i\beta_2} \end{pmatrix} \tag{2a}$$

and

$$\langle \vec{\tau} \cdot \vec{\Delta}_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R} e^{i\alpha_{L,R}} & 0 \end{pmatrix} . \tag{2b}$$

Two of the four phases β_1, β_2, α_L and α_R can be rotated away, but in general two remain. Of course, more Higgs multiplets could be added, but the above choice is sufficient for our purposes.

The Higgs potential generally admits a solution[2] with $v_L \ll k, k' \ll v_R$. In terms of these vacuum expectation values and $g = g_L = g_R$, the charged gauge boson masses are approximately

$$M_L^2 \simeq \frac{1}{2} g^2 (k^2 + k'^2) \tag{3a}$$

and

$$M_R^2 \simeq g^2 v_R^2 \ . \tag{3b}$$

In accordance with experiment[4] and theoretical arguments[14] we assume the mixing angle ξ between the left- and right-handed sectors, defined by

$$\tan 2\xi = \frac{2kk'}{v_R^2} \tag{4}$$

is small, although we need not work in the limit where k' is much smaller than k.

We are particularly interested in the neutral Higgs fields and their couplings to quarks. Of the eight in the original Lagrangian, two are "eaten" to become the longitudinal components of the massive neutral gauge bosons, Z_L^0 and Z_R^0. Of the six physical scalars, one field develops a mass comparable to the usual $SU(2)_L$ mass scale and just corresponds to the standard model Higgs boson with flavor-conserving couplings. The other five develop masses characteristically of order v_R. Two combinations of the fields ϕ_i have comparable large ($O(v_R)$) masses and have flavor-changing couplings to quarks. We take the masses of these latter two Higgs to be equal in the ensuing analysis and refer to a single mass M_H. The remaining three Higgs bosons involve primarily the fields $\Delta_{L,R}$ which don't couple to quarks.[11]

The quark mass matrices arise through Yukawa couplings to Φ and $\tilde{\Phi}$:

$$\mathcal{L}_Y = F\,\bar{Q}_L^0 \Phi Q_R^0 + G\bar{Q}_L^0 \tilde{\Phi} Q_R^0 + \text{h.c.} \tag{5}$$

where the 3×3 matrices F and G are Hermitian, and the quantities

$$Q_{L,R}^0 = \begin{pmatrix} P_{L,R}^0 \\ N_{L,R}^0 \end{pmatrix} ,$$

with generation labels suppressed, are doublets of charge $2/3\,e$ and $-1/3\,e$ quarks, P and N respectively. The superscript zero indicates the fields are weak eigenstates. When the Higgs fields develop their vacuum expectation values, the mass matrices for charge $2/3\,e$ and $-1/3\,e$ becomes

$$M_P = F\,ke^{i\beta_1} + Gk'e^{-i\beta_2} \tag{6a}$$

and

$$M_N = F\,k'e^{i\beta_2} + Gke^{-i\beta_1} \ . \tag{6b}$$

These 3×3 matrices can be diagonalized by biunitary transformations,

$$U_L^+ M_P U_R = D_P \tag{7a}$$

$$V_L^+ M_N V_R = D_N \ , \tag{7b}$$

where $D_{P,N}$ are diagonal matrices whose eigenvalues are the masses and whose eigenvectors are the mixtures of bare quark fields which correspond to the physical quarks. Writing the relation between weak eigenstates and mass eigenstates shows that the Kobayashi-Maskawa[15] (K-M) mixing matrices are simply

$$K_L = U_L^{+} V_L \tag{8a}$$

and

$$K_R = U_R^{+} V_R . \tag{8b}$$

The most general such theory with completely independent K-M matrices on the left and the right is not very esthetic and it is difficult to draw conclusions about it because of the large number of unspecified parameters. We will consider two particular classes of such theories which are most often treated in the literature.

First, there is the case of Hermitian Yukawa coupling matrices and real vacuum expectation values for the ϕ_i. M_P and M_N are then also Hermitian and can be diagonalized by a single unitary matrix, *i.e.* $U_L = U_R$ and $V_L = V_R$, and consequently $K_L = K_R$. The result is a "manifest" LRS theory with the same couplings of the charged bosons W_L and W_R to quarks.

However one must be careful to note that the diagonal mass matrices D_P and D_N do not necessarily have positive eigenvalues.[16] If we absorb the minus signs in the diagonal mass matrix into the quark fields, then this is equivalent to making bi-unitary transformations on the mass matrices and the relation between K_R and K_L becomes

$$K_R = A_P K_L A_N , \tag{9}$$

where A_N and A_P are diagonal matrices with elements ± 1. In other words, if we want positive masses and to put K_L in standard form, then K_R is related to K_L by Eq. (9). Mohapatra *et al.*[8] considered the special case where $A_N = A_P = \pm 1$.

We will treat this, as well as the more general case in Eq. (9), but designate even the more general case as a manifest LRS theory.

The second case of interest is that where the Yukawa coupling matrices are real and symmetric while the vacuum expectation values are complex. Thus CP as well as parity is spontaneously broken. This will be called a pseudo-manifest (or charge conjugation conserving[12]) LRS theory. Harari and Leurer[12] have argued that the charge conjugation conserving version of an LRS theory is in fact the preferred one. In this case $K_R = K_L^*$. However, quark phases such that this is true may not allow K_L to be written in standard form. Again we can absorb extra phases into the quark fields, but now

$$K_R = B_P^* K_L^* B_N \tag{10}$$

where the 3×3 matrices B_P and B_N are diagonal unitary matrices, *i.e.* with elements $e^{i\alpha_q}$, $q = u, c, t$ and d, s, b respectively.

To derive the flavor-changing neutral Higgs couplings, we return to Eq. (5) and rewrite it in terms of quark mass eigenstates, K_L, K_R, and Higgs' vacuum expectation values as

$$\begin{aligned} \mathcal{L}_Y = \frac{1}{(k^2 - k'^2)} \Big\{ & \bar{N}_L (K_L^+ D_P K_R) N_R (k e^{-i\beta_1} \phi_2 - k' e^{i\beta_2} \phi_1^*) \\ & + \bar{P}_L (K_L D_N K_R^+) P_R (k e^{i\beta_1} \phi_2^* - k' e^{-i\beta_2} \phi_1) \Big\} \\ & + \text{h.c.} \, , \end{aligned} \tag{11}$$

where flavor diagonal terms have been dropped. Specifically for neutral meson systems, the effective Lagrangian for neutral Higgs exchange in the process

$\bar{q}_1 q_2 \to \bar{q}_2 q_1$ is

$$\mathcal{L}_{\text{eff}} \simeq -\sqrt{2}\,\frac{G_F}{M_H^2}\left[\frac{k^2+k'^2}{k^2-k'^2}\right]^2 \Lambda_{12}\Lambda'_{12}(\bar{q}_{1L}q_{2R}\bar{q}_{1R}q_{2L}+\bar{q}_{1R}q_{2L}\bar{q}_{1L}q_{2R}) \qquad (12)$$

where for charge $-e/3$ quarks

$$\Lambda_{12} = (K_L^+ D_P K_R)_{\bar{q}_1,q_2} \qquad \Lambda'_{12} = (K_R^+ D_P K_L)_{\bar{q}_1,q_2}\ , \qquad (13)$$

We have assumed that the two flavor-changing Higgs bosons have a common mass, M_H.

In manifest and pseudo-manifest LRS theories Λ and Λ' are closely related: in a manifest LRS theory they are equal, up to a possible sign, while in a pseudo-manifest theory they are complex conjugates, up to an overall phase. With the original representation[15] of K_L as

$$K_L = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix}\ , \qquad (14)$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$, we explicitly have in the manifest LRS theory:

$$\begin{aligned}
\Lambda_{\bar{s}d} = \pm\Lambda'_{\bar{s}d} &= \sum_{q=u,c,t} (K_L^+)_{sq} m_q (K_R)_{qd} \\
&= \pm\Big[-m_u s_1c_1c_3 \pm m_c s_1c_2(c_1c_2c_3 - s_2s_3e^{-i\delta}) \pm m_t s_1s_2(c_1s_2c_3 + c_2s_3e^{-i\delta})\Big] \\
\Lambda_{\bar{b}d} = \pm\Lambda'_{\bar{b}d} &= \sum_{q=u,c,t} (K_L^+)_{bq} m_q (K_R)_{qd} \\
&= \pm\Big[-m_u s_1c_1s_3 \pm m_c s_1c_2(c_1c_2s_3 + s_2c_3e^{-i\delta}) \pm m_t s_1s_2(c_1s_2s_3 - c_2c_3e^{-i\delta})\Big]
\end{aligned} \qquad (15)$$

and in the pseudo-manifest LRS theory:

$$\Lambda_{\bar{s}d} = e^{i(\alpha_d-\alpha_s)}\Lambda'^{*}_{\bar{s}d} = \sum_{q-u,c,t} (K_L^{+})_{sq} m_q (K_R)_{qd}$$

$$= \Big[-m_u s_1 c_1 c_3 e^{-i\alpha_u} + m_c s_1 c_2 (c_1 c_2 c_3 - s_2 s_3 e^{-i\delta})\, e^{-i\alpha_c}$$

$$+ m_t s_1 s_2 (c_1 s_2 c_3 + c_2 s_3 e^{-i\delta}) e^{-i\alpha_t}\Big] e^{i\alpha_d}$$

$$\Lambda_{\bar{b}d} = e^{i(\alpha_d-\alpha_b)}\Lambda'^{*}_{\bar{b}d} = \sum_{q=u,c,t} (K_L^{+})_{bq} m_q (K_R)_{qd} \tag{16}$$

$$= \Big[-m_u s_1 c_1 s_3 e^{-i\alpha_u} + m_c s_1 c_2 (c_1 c_2 s_3 + s_2 c_3 e^{-i\delta})\, e^{-i\alpha_c}$$

$$+ m_t s_1 s_2 (c_1 s_2 s_3 - c_2 c_3 e^{-i\delta})\, e^{-i\alpha_t}\Big] e^{i\alpha_d}\ .$$

In the next sections we will examine the neutral K and neutral B meson mass differences, employing Eqs. (12), (15) and (16) to calculate the flavor-changing neutral Higgs contributions.

3. The Neutral K Meson System

The short-distance contribution to the $K^0 - \bar{K}^0$ mixing amplitude involving the charm quark is known to be of the correct sign and roughly the right magnitude[17] to explain the observed mass difference ΔM_K. While there are indications that there may also be comparable long-distance contributions,[18] other effects which would result in contributions much larger than the observed magnitude of ΔM_K are presumed to be unacceptable. In particular, this is the kind of prohibition which was used by Beall *et al.*[6] on the contribution involving W_L, W_R, and charmed quarks to put a lower bound of 1.6 TeV on M_R.

With no t quark and for neutral Higgs boson masses of several hundred GeV, the flavor-changing couplings given in Eqs. (15) and (16) give contributions through tree level Higgs exchange diagrams which are 10^2 to 10^4 times the measured value of ΔM_K. With the t quark present, but with M_H still only several hundred GeV, there is in principle a way to get around this unacceptably large contribution, *i.e.* by having cancellations between the terms involving m_c and m_t so as to reduce the neutral flavor-changing Higgs coupling effectively to zero. This is in fact what Mohapatra *et al.*[8] did in order to get a much less stringent limit on M_R than Beall *et al.*[6] in a manifest LRS theory. By using particular values of the K-M mixing angles, the neutral Higgs' flavor-changing couplings are much reduced, and the remnant contribution to ΔM_K is used to cancel the other potentially large contribution from the box diagram involving W_L and W_R. We previously showed[9] that the resulting constraints on the K-M angles needed by Mohapatra *et al.*[8] are inconsistent with experimental information from B meson decays. It is useful to give an updated version of the argument.

Assuming positive masses in the diagonalized mass matrix, the product of neutral Higgs couplings entering the relevant quark level process $\bar{s}d \to \bar{d}s$ is from Eq. (15)

$$\Lambda_{\bar{s}d}\Lambda'_{\bar{s}d} = \left[-m_u s_1 c_1 c_3 + m_c s_1 c_2(c_1 c_2 c_3 - s_2 s_3 e^{-i\delta}) + m_t s_1 s_2(c_1 s_2 c_3 + c_2 s_3 e^{-i\delta})\right]^2 . \tag{17}$$

Setting the real part, which contributes to the mass difference, to zero gives

$$\mathrm{Re}\left\{\left[m_c + m_t s_2(s_2 + s_3 e^{-i\delta})\right]^2\right\} = 0 , \tag{18}$$

in the very good approximation of small angles θ_i, and neglecting m_u compared to m_c and m_t. The corresponding constraint due to the imaginary part of the $K^0 - \bar{K}^0$ mass matrix (which is related to ϵ, the CP violation parameter) forces δ to be very close to 0^0 or 180^0. Only $\delta \approx 180^0$ allows Eq. (18) to be satisfied, and setting $\cos\delta = -1$ gives

$$\frac{m_c}{m_t} + s_2^2 - s_2 s_3 = 0 , \tag{19}$$

i.e. the equation of a hyperbola in the $s_3 - s_2$ plane whose asymptotes are the lines $s_2 = s_3$ and $s_2 = 0$, and with a minimum value of $s_3 = 2(m_c/m_t)^{1/2}$.

The relevant piece of information[19] from B decay is the upper limit on $\Gamma(b \to ue\bar{\nu})$ compared to $\Gamma(b \to ce\bar{\nu})$:

$$\frac{\Gamma(b \to ue\bar{\nu})}{\Gamma(b \to ce\bar{\nu})} < 0.05 . \tag{20}$$

Converted into a statement on K-M angles this reads

$$\frac{(s_1 s_3)^2}{F(m_c/m_b)|s_3 + s_2 e^{i\delta}|^2} < 0.05 , \tag{21}$$

where the factor of $F(m_c/m_b)$ takes account of the smaller phase space available in $b \to ce\bar{\nu}$ because of the charm quark mass. Rewriting Eq. (21) in terms of $a^2 = s_1^2/[0.05\, F(m_c/m_b)]$, we have

$$s_2^2 + 2c_\delta s_2 s_3 + (1 - a^2)s_3^2 > 0 \tag{22}$$

We use the value[20] $a^2 = 2.24$. To satisfy the inequality, s_3/s_2 can assume positive values up to the root of the quadratic at $[c_\delta + (c_\delta^2 + a^2 - 1)^{1/2}]/(a^2 - 1)$. For $c_\delta \approx -1$, this root is 0.40, so that $0 \leq s_3/s_2 < 0.40$ or

$$s_2 > 2.5\, s_3 \ . \tag{23}$$

Thus the constraint in Eq. (20) from B decay forces s_2 and s_3 into a region which does not overlap with that where $s_2 < s_3$, as demanded by Eq. (19) which makes the $s \leftrightarrow d$ flavor-changing Higgs coupling vanish.

In the more general case of a manifest LRS theory with positive or negative masses in the diagonalized mass matrix, the above argument does not go through; *i.e.*, the vanishing of the flavor-changing Higgs coupling does not force $s_2 < s_3$ in contradiction to constraints from B decay. However, there are other arguments that can be made.

We recall that in the general manifest LRS theory if we neglect m_u compared to m_c and m_t and take the θ_i small, then the neutral $s \leftrightarrow d$ flavor-changing Higgs coupling is from Eq. (15)

$$\Lambda_{sd} = \pm \Lambda'_{sd} = \pm s_1 \Big[m_c \pm m_t s_2 (s_2 + s_3 e^{i\delta}) \Big] \ . \tag{24}$$

In the pseudo-manifest LRS theory we correspondingly have from Eq. (16)

$$\Lambda_{sd} = e^{i(\alpha_d - \alpha_s)} \Lambda'^{*}_{sd} = e^{i(\alpha_d - \alpha_c)} s_1 \Big[m_c + e^{i(\alpha_c - \alpha_t)} m_t s_2 (s_2 + s_3 e^{-i\delta}) \Big] \ . \tag{25}$$

We see that the general manifest LRS coupling can be treated as a special case of the pseudo-manifest LRS coupling with phases adjusted to give real factors of ± 1. Furthermore if we demand that the tree diagram involving neutral Higgs exchange not give an unacceptably large contribution to either the real (ΔM_K) or imaginary (ϵ) part of the $K^0 - \bar{K}^0$ transition amplitude, then the absolute magnitude of the Higgs contribution is restricted. Therefore, we demand $|\Lambda_{sd}| = 0$ for Higgs masses of several hundred GeV. For either Eq. (24) or (25) this requires

$$|s_2(s_2 + s_3 e^{-i\delta})| = m_c/m_t \ . \tag{26}$$

First we recall that the upper limit on $(b \to u)/(b \to c)$ in Eq. (20) implies that

$$|s_3 + s_2 e^{i\delta}| = |s_2 + s_3 e^{-i\delta}| < a\, s_3 \tag{27}$$

where $a^2 = 2.24$ from the present experimental limit.[19,20] Equations (26) and (27) imply that

$$\frac{m_c}{m_t} < a\, s_2 s_3 \tag{28}$$

and that

$$\left(\frac{a-1}{a}\right)\frac{m_c}{m_t} \le s_2^2 \le \left(\frac{a+1}{a}\right)\frac{m_c}{m_t} \ . \tag{29}$$

Equation (29) bounds s_2 between numbers which are of order $(m_c/m_t)^{1/2}$, a characteristic dependence on quark masses which is familiar from attempts to calculate mixing angles in terms of quark masses and *vice versa*.[21]

While satisfying Eq. (29) is already excluded for a meaningful range of top quark masses given information on the b lifetime, a stronger result is obtained by going back to Eq. (26) and directly inserting the b lifetime to bound the mixing angles. We get the relevant information from the relation

$$\frac{1}{\tau_b} = \frac{\Gamma(b \to ce\bar{\nu})}{BR(b \to ce\bar{\nu})} = \frac{|(K_L)_{cb}|^2}{BR(b \to ce\bar{\nu})} \frac{G_F^2 M_b^5}{192\pi^3} F(m_c/m_b) , \tag{30}$$

where $(K_L)_{cb} = s_3 + s_2 e^{i\delta}$ is the element of the K-M matrix relevant to $b \to c$. We will use the measured semileptonic branching fraction.[19] Choosing masses so as to make the resulting mixing angles as large as possible[20] (to make the resultant restriction on m_t as weak as possible) we find

$$|s_2 + s_3 e^{-i\delta}| = |s_3 + s_2 e^{i\delta}| = 0.059\ (10^{-12}\text{sec}/\tau_b)^{1/2} \tag{31}$$

from Eq. (30) and

$$s_3 < 0.040\,(10^{-12}\text{sec}/\tau_b)^{1/2} \tag{32}$$

from Eq. (21). Consequently the maximum value of $|s_2(s_2 + s_3 e^{-i\delta})|$ is 0.0058 $(10^{-12}\text{sec}/\tau_b)$, and Eq. (26) yields the bound

$$m_t > 172\ m_c(\tau_b/10^{-12}\,\text{sec}) . \tag{33}$$

Thus in either the manifest or pseudo-manifest LRS theory, the present measurements of the b lifetime ($1.8 \pm 0.6 \pm 0.4 \times 10^{-12}$sec from MAC[22] and $1.2^{+0.45}_{-0.36} \pm 0.3 \times 10^{-12}$sec from MkII[23]) require $m_t \gtrsim 250$ GeV if the flavor-changing neutral Higgs coupling is to vanish. For values of m_t smaller than this, the tree level neutral Higgs diagrams give an unacceptably large contribution to ΔM_K and/or ϵ. If the neutral Higgs contribution is to be less than or equal in magnitude[24] to ΔM_K, then $M_H \gtrsim 8$ TeV in vacuum insertion approximation for the relevant matrix elements when $|s_2(s_2 + s_3 e^{i\delta}) m_t| \ll m_c$. Even when $m_t \approx$ 125 GeV, $M_H \gtrsim 4$ TeV in the vacuum insertion approximation.

4. The Neutral B Meson System

For the neutral B meson system the relevant flavor-changing Higgs coupling is that involving $b \leftrightarrow d$. Again neglecting m_u compared to m_c and m_t, Eqs. (15) and (16) becomes

$$\Lambda_{\bar{b}d} = \pm \Lambda'_{\bar{b}d} = \pm s_1 \Big[m_c (s_3 + s_2 e^{-i\delta}) \pm m_t s_2 e^{-i\delta} \Big] \tag{34}$$

and

$$\Lambda_{\bar{b}d} = e^{i(\alpha_d - \alpha_b)} \Lambda'^{*}_{\bar{b}d} = e^{i(\alpha_d - \alpha_c)} s_1 \Big[m_c (s_3 + s_2 e^{-i\delta}) - e^{i(\alpha_c - \alpha_t)} m_t s_2 e^{-i\delta} \Big] \tag{35}$$

in the manifest and pseudo-manifest LRS theories respectively. Since the coefficients of the terms involving m_c and m_t are $s_3 + s_2 e^{-i\delta}$ and s_2, aside from phase factors, it is clear that no complete cancellation between them is possible: the information from B decays presented above shows that $|s_3 + s_2 e^{-i\delta}|$ and s_2 are of the same order of magnitude while $m_t \gg m_c$ from experiment. The term involving m_t will completely dominate $\Lambda_{\bar{b}d}$ and the only way to keep the tree level neutral Higgs exchange diagram from inducing an undesireably large $B^0 - \bar{B}^0$ mixing amplitude is by raising M_H.

To explore this quantitatively we recall from Eq. (12) that the effective Hamiltonian for the neutral Higgs contribution to $b\bar{d} \to \bar{d}b$ is

$$\mathcal{H}_{\text{eff}}(H^0) \simeq \frac{\sqrt{2} G_F}{2 M_H^2} \Lambda_{\bar{b}d} \Lambda'_{\bar{b}d} \Big(\bar{b} d \bar{b} d - \bar{b} \gamma_5 d \bar{b} \gamma_5 d \Big) \,. \tag{36}$$

As a result,

$$\begin{aligned} \Delta M_B(H^0) &= M_{B_S} - M_{B_L} = 2 |\langle B^0 | \, \mathcal{H}_{\text{eff}}(H^0) \, | \bar{B}^0 \rangle| \\ &\simeq \frac{\sqrt{2} G_F}{M_H^2} (s_1 s_2 m_t)^2 |\langle B^0 | \, \bar{b} d \bar{b} d - \bar{b} \gamma_5 d \bar{b} \gamma_5 d \, | \bar{B}^0 \rangle| \,. \end{aligned} \tag{37}$$

A standard evaluation[8,11] of the matrix element gives

$$\langle B^0|(\bar{b}d)(\bar{b}d)|\bar{B}^0\rangle = \frac{B_B f_B^2 M_B}{12}\left(\frac{-M_B^2}{(m_b+m_d)^2}+1\right) \tag{38a}$$

and

$$\langle B^0|(\bar{b}\gamma_5 d)(\bar{b}\gamma_5 d)|\bar{B}^0\rangle = \frac{13 B_B f_B^2 M_B}{12}\left(\frac{-M_B^2}{(m_b+m_d)^2}-\frac{1}{13}\right), \tag{38b}$$

where B_B is a factor which is unity in the vacuum insertion approximation, f_B is the analogue of the pion or kaon decay constants f_π or f_K, M_B the B meson mass, and m_b and m_d the b and d current quark masses respectively. The expression for ΔM_B now becomes

$$\Delta M_B = \frac{\sqrt{2}G_F}{M_H^2}(s_1 s_2 m_t)^2 B_B f_b^2 M_B\left(\frac{M_B^2}{(m_b+m_d)^2}+\frac{1}{6}\right), \tag{39}$$

and therefore

$$\left(\frac{\Delta M_B}{\Gamma_B}\right)^2 = 3.0\left(\frac{1\,TeV}{M_H}\right)^4\left(\frac{m_t}{35\,GeV}\right)^4 B_B^2\left(\frac{f_B}{f_K}\right)^4\left(\frac{M_B^2}{(m_b+m_d)^2}+\frac{1}{6}\right)^2 \times\left[\frac{s_2}{0.099\,(10^{-12}\text{sec}/\tau_b)^{1/2}}\right]^4 . \tag{40}$$

Since for such a heavy quark $M_B \approx m_b + m_d \approx m_b$, the next to last factor should be close to unity. We also expect $B_B = O(1)$. We have normalized various quantities to nominal values in Eq. (40). In particular, we expect[25] $f_B \approx f_K$ ($\approx f_\pi$) and we have normalized s_2 to its maximum value in terms of the b lifetime from Eqs. (31) and (32).

To connect the value of $(\Delta M_B/\Gamma)$ quantitatively with the amount of $B^0-\bar{B}^0$ mixing, we recall that the latter will give rise to events with same-sign dileptons when both B mesons produced in e^+e^- collisions decay semileptonically. Since it is expected that CP violation will be small, the number of same sign dileptons divided by all dileptons is[26]

$$\frac{\sigma(\ell^+\ell^+)+\sigma(\ell^-\ell^-)}{\sigma(\ell^+\ell^-)+\sigma(\ell^-\ell^+)+\sigma(\ell^+\ell^+)+\sigma(\ell^-\ell^-)} \approx \frac{2r}{(1+r)^2} \tag{41}$$

where

$$r = \frac{(\Delta M_B)^2+(\Delta\Gamma_B/2)^2}{2\Gamma_B^2+(\Delta M_B)^2-(\Delta\Gamma_B/2)^2} \tag{42}$$

and ΔM_B and $\Delta\Gamma_B$ are the $B_S^0 - B_L^0$ mass and width differences respectively (Γ_B is the average width).

The present experimental limit[27] of being inconsistent with complete mixing means[28] that $(\Delta M_B/\Gamma_B)^2 \lesssim 1$. If $m_t \approx 35$ GeV and s_2 is close to its maximum value, Eq. (40) requires $M_H \gtrsim 1$ TeV. ($M_H \gtrsim 200$ GeV for the minimum value of s_2.)

However, from the previous section on the neutral K system we already know that vanishing of the $s \leftrightarrow d$ flavor-changing coupling is impossible given the b lifetime unless $m_t \gtrsim 250$ GeV. For values of m_t less than this, the neutral K system constraint already forces M_H to be of order 8 TeV. So we need be concerned here with $m_t \gtrsim 250$ GeV, in which case even the minimum value of s_2 allowed by the b lifetime and $(b \to u)/(b \to c)$ forces $M_H \gtrsim 2$ TeV if $(\Delta M_B/\Gamma_B)^2 \lesssim 1$. If s_2 is near its maximum allowed value, then $M_H \gtrsim 10$ TeV.

5. Conclusion

In the preceding sections we have investigated left-right symmetric gauge theories with a particular eye to the effects caused by the flavor-changing couplings of neutral Higgs particles in the theory. The potentially disastrous consequences of such couplings can be avoided either by adjusting parameters (in particular K-M angles) to make the relevant couplings vanish, or by raising the offending Higgs masses sufficiently high so as to make the effect on measurable low energy processes arbitrarily small.

The route of adjusting parameters so as to make the $s \leftrightarrow d$ flavor-changing coupling (almost) vanish was taken by Mohapatra *et al.*[8] They then used the very small remnant of this flavor-changing coupling to cancel against other potentially large contributions to ΔM_K coming from the box diagram involving W_R, W_L and heavy quarks. In this way they could circumvent restrictions on the size of this latter contribution and an ensuing lower bound of 1.6 TeV on M_R. Both M_R and M_H could then be several hundred GeV. We have shown, in an updated version of the argument in our earlier short paper,[9] that the range of K-M angles needed by Mohapatra *et al.*[8] is ruled out by information from b decays, in particular the upper limit on $(b \rightarrow ue\bar{\nu})/(b \rightarrow ce\bar{\nu})$.

In the present paper we have generalized our argument further to cover not only manifest LRS theories, but also pseudo-manifest (or charge-conjugation conserving) LRS theories where both parity and charge conjugation invariance (and therefore CP) are restored at very high energies. By incorporating new information on the b lifetime we have shown that with $m_t \lesssim 250$ GeV, the $s \leftrightarrow d$ flavor-changing neutral Higgs coupling cannot be made to vanish in such theories. Therefore, in either manifest or pseudo-manifest LRS theories the relevant neutral Higgs mass must be raised to avoid a disastrously large contribution to ΔM_K and/or ϵ. If the flavor-changing neutral Higgs contribution is set to be less than or equal in magnitude to the observed ΔM_K, then $M_H \gtrsim 8$ TeV.

There is still the out[29] of having $m_t \gtrsim 250$ GeV. However, by considering $B^0 - \bar{B}^0$ mixing we have been able to show that experimental indications of the lack of complete mixing imply that for $m_t \gtrsim 250$ GeV, M_H must be greater than about 2 TeV in either the manifest or pseudo-manifest LRS theories.

Thus we find that independent of the value of m_t, the mass of the flavor-changing Higgs bosons must be in the multi-TeV region in order to prevent unacceptably large $K^0 - \bar{K}^0$ or $B^0 - \bar{B}^0$ transition amplitudes from occuring. While the mass of W_R is not uniquely connected to that of the neutral Higgs which has flavor-changing couplings, as discussed in Section 2 both are expected to have masses of the same order, *i.e.* the mass scale (v_R) at which parity (and possibly charge conjugation) symmetry are restored. So we expect M_R to be in the several TeV range as well, in agreement with the argument of Beall *et al.*[6] based on the short-distance contribution to ΔM_K involving W_R. The theoretical evidence, in short, increasingly favors both the right-handed W and flavor-changing Higgs to have masses above[30] a TeV if we have manifest or pseudo-manifest left-right symmetry at all.

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24. When the heavy neutral flavor-changing Higgs bosons have comparable

masses and there is no extra relative phase between the s and d quark fields from A_N in Eq. (9) or B_N in Eq. (10), the sign of the contribution of the neutral Higgs tree level graph to ΔM_K is opposite to the standard model contribution and to that of experiment.

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28. Assuming equal semileptonic branching ratios for the B^0 and B^- and a ratio of production cross sections of 40:60 at the Υ'''

$$\frac{\sigma(\ell^+\ell^+)+\sigma(\ell^-\ell^-)}{\sigma(\ell^+\ell^-)+\sigma(\ell^-\ell^+)+\sigma(\ell^+\ell^+)\sigma(\ell^-\ell^-)} = -0.23 \pm 0.30$$

from Ref. 27. At the two standard deviation level this implies that $(\Delta M_B/\Gamma_B)^2 < 1$.

29. The lower bound from the neutral K system on M_H falls with increasing m_t, while that from the neutral B system rises. For $m_t \approx 200$ GeV the bounds are the same and imply $M_H \gtrsim 1.6$ TeV.
30. Indeed, if CP violation is largely due to relative phases between K_L and K_R in the pseudo-manifest LRS theories, Harari and Leurer (Ref. 12) find an upper bound on the mass of W_R of 21 TeV.