Constraints from $b \to s\gamma$ on the left-right symmetric model

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Recent results from the CLEO Collaboration on both inclusive and exclusive radiative B decays are used to constrain the parameter space of two versions of the left-right symmetric model. In the first scenario, when the left- and right-handed Cabibbo-Kobayashi-Maskawa mixing matrices are equal, $V_L = V_R$, the radiative B decay data are shown to lead to strong bounds on the $W_L - W_R$ mixing angle that are quite insensitive to either the top quark or W_R mass. The second scenario examined is that of Groanu and Wakaizumi wherein b-quark decays proceed only via right-handed currents and V_L and V_R are quite distinct. For this model, the combined constraints from Fermilab Tevatron W_R searches, the B lifetime, and radiative B decays lead to a very highly restricted allowed range for the $W_L - W_R$ mixing angle.

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While the standard model (SM) of strong and electroweak interactions is in very good agreement with all existing experimental data [1], there are many reasons to believe that new physics (NP) must exist not far above the scale currently being probed at the SLAC Linear Collider (SLC), CERN e^+e^+ collider (LEP), and Fermilab Tevatron collider. Although we do not know what form this NP might take, there are a vast number of proposals in the literature. The best that we can do in the "prediscovery" ear is to use existing data to restrict the prosperities of this NP and to continue searching. While colliders provide us with the capability to directly produce signatures of NP, a complementary approach is to hunt for NP indirectly through high precision measurements and the observation of rare processes. An excellent working example of such a process has been provided to us by the CLEO Collaboration [2], which has recently observed the exclusive decay $B \to K^*\gamma$ with a branching fraction of $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$ and has placed an upper limit on the inclusive quark-level process of $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95% C.L. Using a conservative estimate for the ratio of exclusive to inclusive decay rates [3], the observation of the exclusive process implies the *lower* bound $B(b \to s\gamma) > 0.60 \times 10^{-4}$ at the 95% C.L. These values are, of course, consistent with SM expectations [4], but can be used to restrict various forms of NP, as has been done in the recent literature [5]. It is important to note that both the upper *as well* as the lower bounds can be used to constrain NP since any model leading to an extremely suppressed rate for this process is already excluded by the CLEO data. Not all of the analyses [5] have taken advantage of this additional constraint.

One scenario of NP which has been popular in the literature for many years and has had many manifestations is the left-right symmetric model (LRSM) [6] based on the extended electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$. Among other things, this model predicts the existence of a heavy, right-handed, charged gauge boson $W_R^\pm$, which can in principle mix through an angle ϕ with the more conventional $W_L^\pm$ present in the SM to form the mass eigenstates $W_{1,2}$. Data from, e.g., polarized μ decay [7] (in the case of light right-handed neutrinos) and universality requirements [8] tell us that the size of this mixing must be reasonably small (less than, say, $|\phi| = 0.05$ or so), but whose exact magnitude depends on the detailed assumptions we make about the other features of the model [9]. As we will see below, the exchange of $W_R^\pm$ within a penguin diagram, in analogy with the SM W exchange, can lead to significant deviations from SM predictions for the $b \to s\gamma$ branching fraction, which is quite sensitive to both the sign and magnitude of ϕ.

In order to numerically determine the branching fraction for $b \to s\gamma$ within the LRSM, there are several sets of parameters whose values we need to address: (i) the mass of the W_R itself; (ii) the ratio of the right-handed to left-handed SU(2) gauge group coupling constants, i.e., $\kappa = g_R/g_L$; (iii) the mixing angle ϕ; and (iv) the numerical values for the elements of the mixing matrix V_R. For the purposes of our discussion below, we will treat ϕ as a free parameter and use the data on the $b \to s\gamma$ decay itself to constrain ϕ as a function of the other degrees of freedom. *If* we assume $V_L = V_R$, then there are several strong constraints on the W_R mass arising from both collider searches [10] as well as the K_l-K_S mass difference [9,11] and it is likely that $M_{W_R} > 1.6\kappa$ TeV. Although this possibility is both simple and attractive, realistic and phenomenologically viable models can be constructed wherein V_R and V_L are quite unrelated as in the scenario of Gronau and Wakaizumi (GW) [12] that we will discuss is more detail below. In such models, at least some of the conventional constraints on the W_R mass can be evaded. However, all such bounds are also dependent on the value of κ, and within the context of grand unified theories, we generally find that $\kappa \leq 1$ [13]. One might naively expect in more general context that this ratio or coupling differs from unity by no more than a factor of 2 or so.

The approach we follow in performing our calculations has already been discussed in our earlier work [14], and we will refer the interested reader to those papers for calculational details. An outline of this approach is as follows. To obtain the $b \to s\gamma$ branching fraction, the inclusive $b \to s\gamma$ rate is scaled to that of the semileptonic decay $b \to Xl\nu$. This removes major uncertainties in the calculation associated with (i) an overall factor of m_b^5 which appears in both expressions and (ii) the various right- and left-handed Cabibbo-Kobayashi-Maskawa (CKM) factors. We then make use of the data on the semileptonic branching fraction [15], which is given by $B(b \to Xl\nu) = 0.108$, to rescale our result. The semileptonic rate is calculated including both phase space (due to the large value of m_c/m_b) and QCD corrections [16] with $m_b = 5$ GeV and $m_c = 1.5$ GeV. The calculation of $\Gamma(b \to s\gamma)$ employs the next-to-leading logarithmic evolution equations for the coefficients of the $b \to s$ transition operators in the effective Hamiltonian due to Misiak [17], the gluon bremsstrahlung corrections of Ali and Greub [18], the leading corrections from heavy quark effective theory (HQET) [19], a running $\alpha_{\rm QED}$ evaluated at the b-quark mass scale, and three-loop evolution of the running α_s matched to the value obtained at the Z scale via a global analysis [1] of all data. As we will see, the bounds we obtain on the parameters of the LRSM are not very sensitive to the remaining uncertainties [20] in the calculation of the $b \to s\gamma$ branching fraction arising from higher order QCD corrections. In what follows we limit our attention to the contributions of the charged gauge bosons to the $b \to s\gamma$ decay rate. In principle, there are potentially other significant contributions in the LRSM owing to the extended nature of the symmetry-breaking sector; i.e., there can be significant contribution from charged Higgs exchange as well as from flavor-changing neutral Higgs boson exchange; we will ignore both these possibilities in the analysis below.

To complete the calculation we use the one-loop matching conditions for the various operators [17] in a form that includes contributions from both the SM and new LRSM operators; i.e., for every "left-handed" operator present in the SM, the existence of light-right symmetry dictates the existence of the corresponding "right-handed" one. The two sets of operators do not mix under QCD evolution and can thus be treated independently. The $b \to s\gamma$ branching fraction can then be expressed as, using $\alpha_{\rm QED}^{-1}(m_b) = 132.7$,

$$B(b \to s\gamma) = \frac{6\alpha_{\rm QED}(m_b)}{\pi(1+Q)} B(b \to cl\nu) \times \frac{|C_{7L}^{\rm eff}|^2 + |C_{7R}^{\rm eff}|^2}{(L_l^2 + R_l^2)[(L_h^2 + R_h^2)f + 2L_h R_h g]} F \ , \quad (1)$$

where $Q(f,g)$ is the QCD (phase space) correction to the semileptonic decay $b \to cl\nu$. While Q as a function of $m_c - m_b$ is given in [16], the explicit forms for f and g are given, e.g., in [21]:

$$f = (1 - y^4)(1 - 8y^2 + y^4) - 24y^4 \ln y \ ,$$
$$g = -2y[(1 - y^2)(1 + 10y^2 + y^4) + 12y^2(1 + y^2)\ln y] \ , \quad (2)$$

where $y = m_c/m_b$. For $y = 0.3$, we obtain $f \simeq 0.520$, $g \simeq -0.236$, and $Q \simeq 2.50[(2/3\pi)\alpha_s(m_b)]$. The factor F denotes the relatively small corrections from HQET and gluon bremsstrahlung mentioned above and are both of order a few percent. Defining $t_\phi = \tan\phi$ and $r = (M_{W_1}/M_{W_2})^2$ (using $M_{W_1} \simeq 80.21$ GeV in numerical calculations), we obtain, for a general LRSM,

$$(L_l^2 + R_l^2)(L_h^2 + R_h^2) = |V_{cb}^L|^2[(1 + rt_\phi^2)^2 + \kappa^2 t_\phi^2(1 - r)^2] + |V_{cb}^R|^2[\kappa^2 t_\phi^2(1 - r)^2 + \kappa^4(r + t_\phi^2)^2] \ , \quad (3)$$

$$2L_h R_h(L_l^2 + R_l^2) = 2\kappa t_\phi(1 - r){\rm Re}(V_{cb}^L V_{cb}^R)[(1 + rt_\phi^2) + \kappa^2(r + t_\phi^2)] \ .$$

(Note that we implicitly assume that the mass of the right-handed neutrino is sufficiently low as to allow its participation in the B decay process and lets us neglect corrections of order $m_{\nu_R}^2/m_b^2$.) $C_{7L,R}^{\rm eff}$ are defined via the low-energy effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{G_F e m_b}{4\sqrt{2}\pi^2} \bar{s}\sigma_{\mu\nu}(C_{7L}^{\rm eff} P_R + C_{7R}^{\rm eff} P_L) b F_{\mu\nu} \ , \quad (4)$$

where $P_{L,R} = (1 \pm \gamma_5)/2$ and whose numerical values are obtained from the operators evaluated at the weak scale ($\simeq M_{W_1}$) via a renormalization group analysis. This analysis is, of course, quite similar to that performed for in the SM case except for the additional operators that are present and have nonzero coefficients at the weak scale. Of course, in either the SM or LRSM, only a few of these weak scale operator coefficients are nonzero to one-loop order. Assuming that the top- (t-)quark contribution dominates the penguin diagrams (as will be the case in the scenarios we examine below), we obtain, in the usual notation,

$$C_{2L}(M_{W_1}) = (1 + rt_\phi^2)(V_{cb}V_{cs}^*)_L \ ,$$
$$C_{2R}(M_{W_1}) = \kappa^2(r + t_\phi^2)(V_{cb}V_{cs}^*)_R \ ,$$
$$C_{10L}(M_{W_1}) = \kappa t_\phi(1 - r)\frac{m_c}{m_b}(V_{cb}^L V_{cs}^{*R}) \ ,$$
$$C_{10R}(M_{W_1}) = C_{10L}(M_{W_1})(L \leftrightarrow R) \ , \quad (5)$$

$$C_{7L}(M_{W_1}) = (V_{tb}V_{ts}^*)_L[A_1(x_1) + rt_\phi^2 A_1(x_2)] + \frac{m_t}{m_b} r t_\phi (V_{tb}^R V_{ts}^{*L})[A_2(x_1) - rA_2(x_2)] \ ,$$

$$C_{7R}(M_{W_1}) = \frac{m_t}{m_b}\kappa t_\phi(V_{tb}^L V_{ts}^{*R})[A_2(x_1) - rA_2(x_2)] + \kappa^2(V_{tb}V_{ts}^*)_R[t_\phi^2 A_1(x_1) + rA_1(x_2)] \ ,$$

where $x_{1,2} = m_t^2/M_{W_{1,2}}^2$. The coefficients of the operators corresponding to the gluon penguin, $C_{8L,R}(M_{W_1})$, can be expressed in a manner similar to $C_{7L,R}(M_{W_1})$ but with $A_i \to B_i$; note that both A_1 and B_1 are the same functions found in the usual SM calculation. Explicitly, we find

$$A_1(x) = -\frac{1}{2}(x-1)^{-4}\left[Q_t\left(\frac{1}{4}x^4 - \frac{3}{2}x^3 + \frac{3}{4}x^2 + \frac{x}{2} + \frac{3}{2}x^2 \ln x\right) + \left(\frac{1}{2}x^4 + \frac{3}{4}x^3 - \frac{3}{2}x^2 + \frac{1}{4}x - \frac{3}{2}x^3 \ln x\right)\right], \quad (6)$$

$$A_2(x) = \frac{1}{2}(x-1)^{-3}\left[Q_t\left(-\frac{1}{2}x^3 - \frac{3}{2}x + 2 + 3x\ln x\right) + \left(-\frac{1}{2}x^3 + 6x^2 - \frac{15}{2}x + 2 - 3x^2 \ln x\right)\right], \quad (7)$$

where $Q_t = \frac{2}{3}$ is the top-quark electric charge and $B_{1,2}(x)$ are given by the terms proportional to Q_t in $A_{1,2}(x)$. An important feature to note in the expressions above is the chiral enhancement, by a factor of $m_t/m_b \sim 30$, of the terms which involve mixing between the W_L and W_R gauge bosons which are proportional to a factor of $t_\phi = \tan\phi$. This implies that the decay rate for $b \to s\gamma$ should be quite sensitive to small values of t_ϕ even when the W_2 is quite massive.

We note in passing that the assumption of top-quark dominance of the penguin diagrams may not always be valid in a general LRSM since, in principal, the values of the elements of both V_L and V_R may conspire to suppress this contribution. This happens, however, in only a very small region of the parameter space since $m_t/m_c > 100$.

Before explicitly considering the numerical results in the LRSM case, we should mention the possibility that the $t\bar{b}$ vertex could have a small right-handed component while still maintaining the SM gauge group; this possibility was recently considered by Fujikawa and Yamada (FY) [25]. (The model is a purely phenomenological one and is not based on any specific gauge theory.) This situation is completely different than the LRSM as the SM W alone carries all of the interactions and a full right-handed mixing matrix V_R is not present. In particular, all other charged-current interactions in the FY model are purely left handed whereas in the LRSM case currents of both chiralities are generally present for all quark flavors. This implies, for example, that the b-quark semileptonic decay is purely left handed in the FY scheme. We thus expect the LRSM and FY scenarios to lead to qualitatively different results for the $b \to s\gamma$ branching fraction.

Let us first consider the situation where $V_L = V_R$; in this case, the implied lower bound on the $b \to s\gamma$ branching fraction plays no role in restricting the LRSM parameters. If we assume that $\kappa = 1$ and M_{W_R} is large, we can ask for the bound on t_ϕ as a function of m_t that results from the CLEO limits; this is shown in Fig. 1 for a W_R of mass 1.6 TeV and which explicitly displays the $b \to s\gamma$ branching fraction as a function of t_ϕ. Here we see the following. (i) The constraint on the value of t_ϕ is relatively insensitive to m_t and, at 95% C.L., lies in the approximate range $-0.02 < t_\phi < 0.005$. These bounds are much more restrictive than what one obtains from either μ decay data ($-0.056 < t_\phi < 0.040$) [7] or universality arguments ($-0.065 < t_\phi < 0.065$) [8]. (ii) For top masses larger than 120 GeV, the $b \to s\gamma$ branching fraction (B) is always found to be in excess of 1.4×10^{-4}. These results are found to be quite insensitive to the particular values chosen for either the W_R mass or κ as long as the W_R is reasonably heavy. One may wonder if in fact we can turn this argument around in order to get a constraint on M_{W_R} itself from the CLEO data. To address this issue, we fix $m_t = 160$ GeV with $\kappa = 1$ and display B for various values of M_{W_R} as a function of t_ϕ as shown in Fig. 2. Here we see that B itself is not very sensitive to the W_R mass for fixed m_t so that no limit is obtainable from this decay mode. Last, for fixed $m_t = 160$ GeV and $M_{W_R} = 1.6$ TeV, we can explore the sensitivity of the resulting bounds on t_ϕ as κ is varied; this is shown in Fig. 3 for $0.6 < \kappa < 2$. As might be expected, the bound strengthens with increasing values of κ, but only weakly so for positive values of t_ϕ. The strengthening of the bounds for negative t_ϕ is much more noticeable. It is clear from these figures that the CLEO results provide an additional important constraint on the LRSM parameters when $V_L = V_R$ is assumed and that QCD uncertainties at the level of 10–20 % will not significantly influence the results we have obtained.

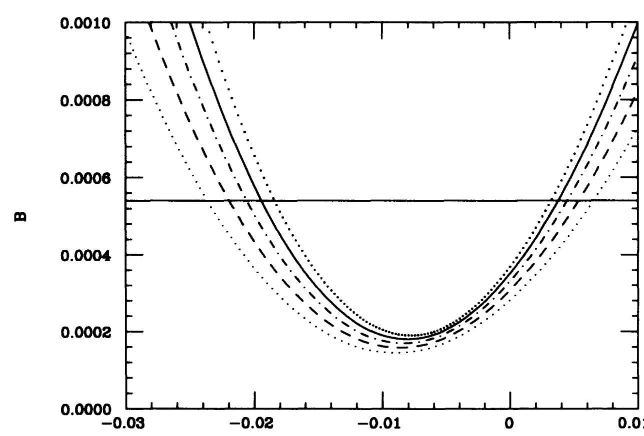

FIG. 1. $b \to s\gamma$ decay mode in the LRSM assuming $V_L = V_R$ as a function of the tangent of the W_L-W_R mixing angle t_ϕ. Here we assume $\kappa = 1$ and a W_R mass of 1.6 TeV for top quark masses of $m_t = 120$ (dotted curve), 140 (dashed curve), 160 (dot-dashed curve), 180 (solid curve), or 200 (square dotted curve) GeV. The horizontal solid line is the CLEO upper bound.

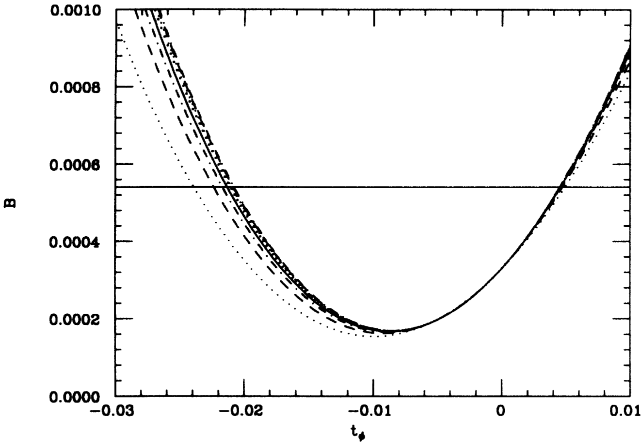

FIG. 2. Same as Fig. 1, but with $m_t = 160$ GeV held fixed and M_{W_R} varied between 300 (lower curve) and 1000 (upper curve) GeV.

Let us now turn to the perhaps more interesting scenario of Gronau and Wakaizumi (GW) wherein B decays proceed *only* via the right-handed currents. For concreteness we take the forms of V_L and V_R as they appear in the original work of GW [12]:

$$V_L = \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} ,$$

$$V_R = \begin{pmatrix} c^2 & -cs & s \\ \frac{s(1-c)}{\sqrt{2}} & \frac{c^2+s^2}{\sqrt{2}} & \frac{c}{\sqrt{2}} \\ \frac{-s(1+c)}{\sqrt{2}} & -\frac{c-s^2}{\sqrt{2}} & \frac{c}{\sqrt{2}} \end{pmatrix} , \tag{8}$$

where λ ($\simeq 0.22$) is the Cabibbo angle and $s \simeq 0.09$. In order to satisfy B lifetime constraints, the parameters in the GW model must satisfy the additional requirement

$$M_{W_R} \leq 416.2\kappa \left[\frac{|V_{cb}^R|}{\sqrt{2}}\right]^{1/2} \text{GeV} \simeq 415\kappa \text{ GeV} , \tag{9}$$

which arises from recent determinations of V_{cb} in the SM [22]. In addition, to satisfy μ decay data, the right-handed neutrino must be sufficiently massive ($\simeq 17$ MeV), but this has little effect on the B decay itself. Of course, a W_R satisfying the above constraint is relatively light and should have a significant production cross section at the Tevatron given the form of V_R. In our earlier work we showed that a W_R in the GW model can satisfy *both* the low-energy and collider bounds provided that $\kappa \geq 1.54$ and $M_R \geq 600$ GeV [10] if we assume that the W_R decays only into the known SM particles as well as the right-handed neutrino. We will respect these conditions when considering the predictions of this model for the $b \to s\gamma$ decay, but we should remember that these collider-based limits are clearly softened if additional decay modes of the W_R are allowed.

First, let us fix both M_{W_R} and κ in order to satisfy the above constraints and examine the predicted value of B in the GW model as a function of t_ϕ; this is shown in Figs. 4 and 5 for various values of m_t. From these two figures we learn that (i) the allowed range of t_ϕ is more tightly restricted in comparison to the $V_L = V_R$ case by *both* the upper and lower CLEO limits, (ii) the bounds are quite insensitive to m_t, and (iii) the value $t_\phi = 0$ is almost excluded by the CLEO lower limit. Further, we see as M_{W_R} is increased (also increasing κ to satisfy the constraints above) that the curves become steeper, and this forces the allowed regions of t_ϕ to become quite pinched and narrow. In the $M_{W_R} = 600$ (800) GeV case, the allowed ranges for t_ϕ are found to be $-0.43 \times 10^{-3} < t_\phi < 0$ and $0.40 \times 10^{-3} < t_\phi < 0.81 \times 10^{-3}$ ($-0.32 \times$

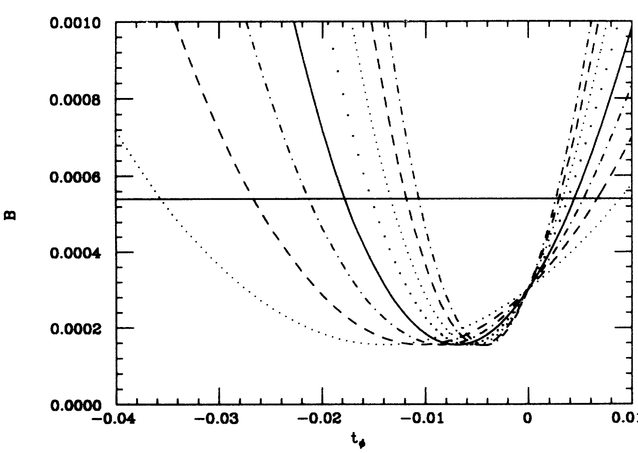

FIG. 3. Same as Fig. 1, but with $m_t = 160$ GeV and $M_{W_R} = 1.6$ TeV with κ varying between 0.6 (leftmost dotted curve) and 2 (innermost dot-dashed curve).

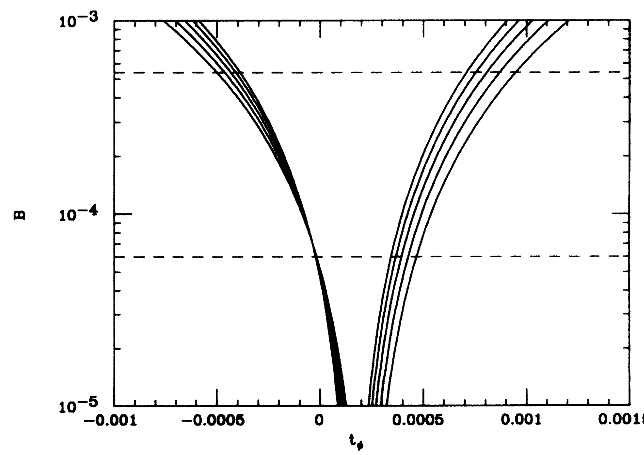

FIG. 4. Predicted values for the branching fraction (B) of the $b \to s\gamma$ decay mode in the Gronau-Wakaizumi version of the LRSM as a function of the tangent of the W_L-W_R mixing angle t_ϕ. In this figure, $\kappa = 1.5$ and $M_{W_R} = 600$ GeV is assumed and the outer- (inner-) most sold line corresponds to $m_t = 120$ (200) GeV and is increased in each case by steps of 20 GeV. The dashed horizontal lines are the CLEO upper and lower bounds.

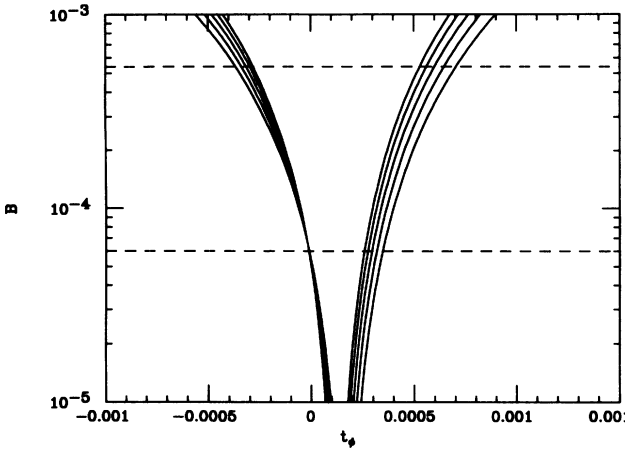

FIG. 5. Same as Fig. 4, but with $\kappa = 2$ and $M_{W_R} = 800$ GeV.

$10^{-3} < t_\phi < 0$ and $0.29 \times 10^{-3} < t_\phi < 0.60 \times 10^{-3}$). To say the least, these ranges are highly restrictive and it is clear that a more precise determination of the value of B may rule out the model as it now stands. To show just how pinched these curves become with increasing M_{W_R}, we fix $m_t = 160$ GeV and let $M_{W_R} = 400\kappa$ GeV while varying κ; this is shown in Fig. 6. Clearly, as M_{W_R} grows, the allowed ranges become *extremely* tight and only a very fine-tuning of the parameters will allow the GW model to remain phenomenologically viable unless other sources of new physics are introduced.

Why do the traditional LRSM and GW scenarios differ in their predictions for the value of the $b \rightarrow s\gamma$ branching fraction? Almost all of the difference can be traced back to the different forms of $V_{L,R}$ in the two cases. If, for example, $V_L = V_R$, then $(V_R)_{cb} \simeq 0.042$, whereas it is approximately 18 times larger in the GW scenario. The change in the forms of V_L and V_R as one flips between these two cases completely changes the weighting of the chiral structure of the quark charged currents. The enhanced strength of the right-handed b-quark coupling in the GW case allows for a complete destructive interference in the amplitude for the decay rate, whereas this does not occur in the case of the conventional LRSM.

It is, of course, possible that a modified version of the GW scheme may be realized by slightly different versions of both V_L and V_R; several such scenarios exist in the literature. Hou and Wyler [23] have, in fact, two distinct versions of these matrices, denoted by I and II. The resulting predictions for the $b \rightarrow s\gamma$ branching fraction B in both scenarios are quite similar and are shown in Figs. 7(a) and 7(b) for $\kappa = 1.5$ and $M_{W_R} = 600$ GeV. (The collider bounds on the W_R in both these scenarios are essentially identical to the original GW model.) Quantitatively, these predictions are very similar to those of the original GW scheme. Quite recently, Hattori *et al.* have proposed another positive version of the GW scenario [24], leading to the predictions for B in Fig. 8, again assuming $\kappa = 1.5$ and $M_{W_R} = 600$ GeV. In this model the "no-mixing" possibility $t_\phi = 0$ is completely excluded by the CLEO data, but otherwise the results

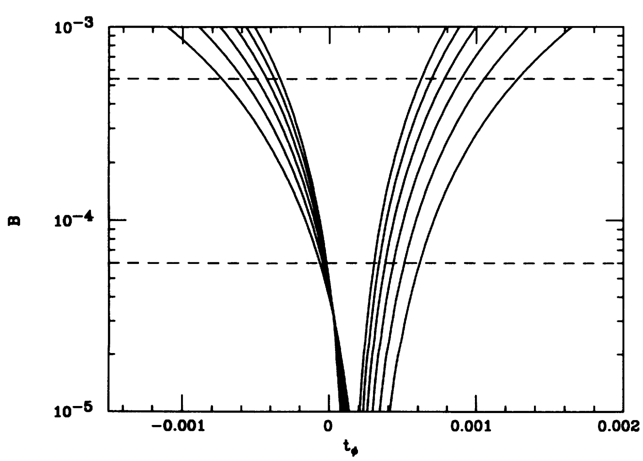

FIG. 6. Same as Fig. 4, but for m_t fixed at 160 GeV and $M_{W_R} = 400\kappa$ GeV. Here κ is varied between 1 and 2 in steps of 0.2 with $\kappa = 1(2)$ corresponding to the outer (inner) curve.

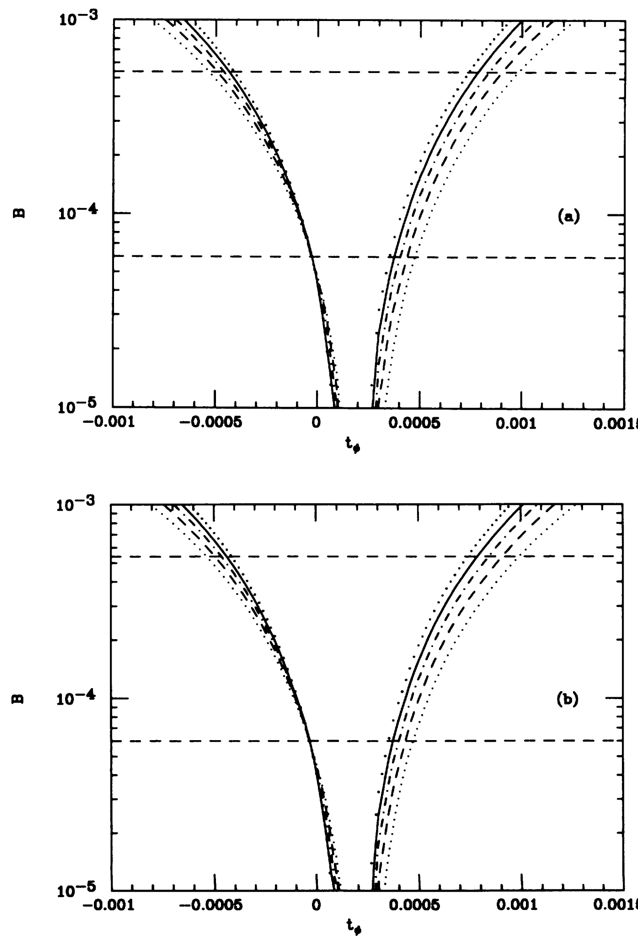

FIG. 7. Predicted values for B in the Hou-Wyler parametrization of V_L and V_R assuming $\kappa = 1.5$ and $M_{W_R} = 600$ GeV. The dotted (dashed, dot-dashed, solid, square dotted) curve corresponds to $m_t = 120$ (140, 160, 180, 200) GeV: (a) version I and (b) version II.

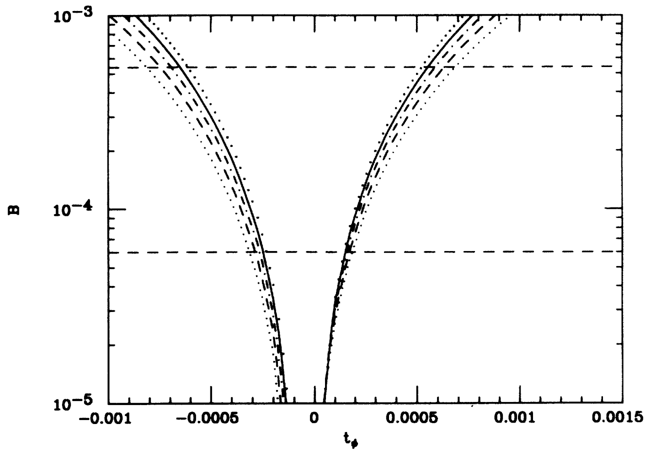

FIG. 8. Same as Fig. 7, but for the parametrization of Hattori *et al.*

are similar to that of the original GW model. It would seem that a general result of the GW approach is to restrict t_ϕ to very small, but most likely nonzero, values. As in the standard GW case, the t_ϕ dependence in both the Hou-Wyler as well as the Hattori *et al.* models becomes somewhat stronger as the W_R mass is increased to 800 GeV and κ is set to 2.

In this paper we have examined the predictions of the left-right symmetric model for the $b \to s\gamma$ branching fraction in the limit where only the $W_L^\pm$ and $W_R^\pm$ gauge bosons contribute to the penguin amplitudes. We examined two specific versions of this model, the first, wherein left-right symmetry is explicit and $V_L = V_R$, and the second, in which the b quark essentially decays only through right-handed currents. This corresponds to models of the kind first constructed by Gronau and Wakaizumi. In the $V_L = V_R$ case, the limits we obtained on the W_L-W_R mixing angle ϕ were found to be relatively independent of the top quark mass and the assumed value of M_{W_R} provided $\kappa = 1$. For fixed top and W_R masses, however, the sensitivity of these constraints to variations in κ was found to be significant. The bounds we obtained on ϕ were comparable to, yet somewhat better than, those obtainable from μ decay data or universality arguments. No limit on M_{W_R} is obtained from these considerations alone, and only the CLEO upper bound was needed to obtain the resulting constraints. In the GW-type scenarios, both upper and lower bounds on the $b \to s\gamma$ branching fraction provided important input and were folded together with additional constraints arising from Tevatron collider searches as well as the B lifetime. Again, the resulting limits on ϕ were relatively m_t independent and extremely tight, falling into two distinct regions in all the cases we examined. An improvement in the CLEO bounds could conceivably rule out this scenario if our assumptions remain valid, except, perhaps, for some extremely fine-tuned cases. Additional penguin contributions in the form of, e.g., Higgs bosons would then be needed to rescue this approach.

Perhaps rare B decays may yet provide us with a signature for new physics beyond the standard model.

Note added. After this manuscript was essentially completed, we received several reports by various authors who have also analyzed the decay rate for $b \to s\gamma$ in the SM with right-handed b-quark couplings as well as in the LRSM [25] for the $V_L = V_R$ case. Where we overlap, the results we have obtained are in agreement with these other authors.

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