Does the *b* Quark Decay Left-Handedly?

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The left-handedness of the b quark weak couplings has not yet been tested experimentally. We present an $SU(2)_L \times SU(2)_R \times U(1)$ model with purely right-handed b decay couplings. We show that the model is consistent with the quite severe existing experimental constraints from B decays, from B^0-$\bar{B}^0$ mixing, from the neutral K mass difference, and from CP violation in the kaon system. We point out a difficulty in distinguishing our scheme from the standard model in semileptonic B decays.

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In the standard model of electroweak interactions the charged-current quark weak couplings are given by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. Several of these couplings were measured in B meson decays [2]. However, the most fundamental property of b quark couplings, i.e., their left-handed chirality, has not yet been demonstrated. It is this property which we question in the present Letter. To stress our point, we will focus on the extreme counter possibility that the observed decays of B mesons are due to purely right-handed couplings of the b quark to the c and u quarks. Right-handed b couplings would not only have direct effects in semileptonic B decays, where the $V-A$ structure has not yet been tested, but they would also affect nonleptonic B decays and would lead to extra contributions in B_d^0-$\bar{B}_d^0$ mixing, in the K_L-K_S mass difference, and in CP violation in the neutral K system. These phenomena are very nicely described in the standard model in terms of the CKM matrix. We will show that they can also be interpreted in terms of purely right-handed b couplings to c and u quarks.

In previous studies of right-handed couplings it was often assumed that the left-handed couplings of the b quark to the c and u quarks were already determined from the observed B decays. The new right-handed interactions were assumed to be small perturbations that essentially do not affect the determination of the CKM matrix elements. Our purpose in raising the somewhat extreme question of purely right-handed b decay couplings is not so much to offer an immediate alternative model to the very successful $SU(2)_L \times U(1)$ theory, rather, we wish to focus on some soft points of the standard model related to B physics which must be settled experimentally and theoretically in order to firmly test the standard model.

A recent review of bounds on right-handed quark weak currents was given by Langacker and Sankar [3]. When analyzed in a general $SU(2)_L \times SU(2)_R \times U(1)$ model [4] the limit on the right-handed gauge boson mass M_R, obtained from various phenomenological constraints, is $M_R^g \equiv (g_L/g_R)M_R > 300$ GeV for left and right gauge couplings g_L, g_R. The mass range in the vicinity of the lower limit is adequate for an interpretation of the measured B decay lifetime in terms of a purely right-handed b-to-c coupling:

$$\beta_g \equiv \frac{g_R^2}{g_L^2}\frac{M_L^2}{M_R^2} \sim |V_{cb}| = 0.042 \pm 0.007 . \quad (1)$$

All our errors should be considered 1σ, although they involve theoretical uncertainties. $|V_{cb}|$ is the apparent value of the CKM matrix element extracted from the B lifetime and from its semileptonic decay branching ratio [5]. Equation (1) provides a reasonable motivation for our scenario, in which the long B-decay lifetime is assumed to be related to the heaviness of W_R rather than to a particularly small CKM mixing parameter.

To set the stage, let us work within the $SU(2)_L \times SU(2)_R \times U(1)$ model, in which the discrete L-R symmetry is not a good symmetry at low energies, $g_R \neq g_L$ [3]. We denote the left- and right-handed quark mixing matrices by V^L and V^R, respectively. V_{ij} stands for the experimental values of the CKM matrix elements obtained in the standard model. Our basic assumption is that V^L has the following form:

$$V^L = \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix} , \quad (2)$$

where θ_C is the Cabibbo angle. Zero mixing between the third family and the other two may result from some family symmetry.

In this model B decays are due to W_R exchange and W_L-W_R mixing. We will use the limits $\beta_g < 0.07$, $|\zeta_g| \equiv (g_R/g_L)|\zeta| < 0.04$. A much more stringent limit on the W_L-W_R mixing parameter ζ_g was obtained [6] from a current-algebra argument which relates $K \to 3\pi$ to $K \to 2\pi$. This limit disregarded, however, CP phases in V^R. A weaker limit, $|\zeta_g| < 0.013$, was obtained in Ref. [3] when large CP phases (maximal or almost maximal) were allowed in V^R. Because of the perhaps questionable assumptions involved in deriving this limit we have somewhat relaxed the limit, consistent with other constraints [3]. To allow for W_R exchange contributions to the observed semileptonic B decays, the mass of the right-handed neutrino must be lighter than $m_b - m_c$. We will assume $m(\nu_R)$ to be sufficiently small not to affect phase space significantly. In all other aspects of semileptonic B decays, which do not directly distinguish between $V-A$ and $V+A$ quark and lepton currents, one must simply replace the standard model values of $|V_{ib}|$ $(i=c,u)$ by $|V_{ib}^R|(\beta_g^2+|\zeta_g|^2)^{1/2}$. This imposes certain constraints on the elements of V^R which we wish to discuss.

The B-decay lifetime, its semileptonic branching ratio, and the bounds $\beta_g < 0.07$, $|\zeta_g| < 0.04$ require

$$|V_{cb}^R|(\beta_g^2+|\zeta_g|^2)^{1/2}=|V_{cb}| \Longrightarrow |V_{cb}^R| > \tfrac{1}{2} \,. \tag{3}$$

The observed hard lepton spectrum in B decays, from a b-to-u transition, implies [5]

$$|V_{ub}^R/V_{cb}^R| = |V_{ub}/V_{cb}| = 0.12 \pm 0.04 \,. \tag{4}$$

Nonleptonic B decays lead to further constraints. Although estimates of hadronic branching ratios depend on models for B decays [7], some approximate ranges for V_{ud}^R, V_{cs}^R can be obtained. The observed decay rates of a variety of two-body B decays (e.g., $B \to D\pi, D\rho, \psi K, DD_s$) agree with the standard model estimates for CKM-unsuppressed processes [2]. Uncertainties of a factor of 2 exist in some of the experimental branching ratios and in the theoretical estimates. When interpreted in terms of our model one may safely use the following ranges:

$$1/\sqrt{2} \le |V_{ud}^R|, |V_{cs}^R| < 1 \,. \tag{5}$$

Since Cabibbo-suppressed decays, such as $B \to DK, D\bar{D}$, have not yet been observed we will assume

$$|V_{us}^R|, |V_{cd}^R| \le \sin\theta_C \,. \tag{6}$$

Equations (3)-(6) and unitarity of V^R give

$$|V_{ud}^R| \approx 1, \quad |V_{td}^R| \le \sin\theta_C \,, \tag{7}$$

$$\begin{gathered} 1/\sqrt{2} \le |V_{cs}^R|, |V_{tb}^R| < \sqrt{3}/2 \,, \\ \tfrac{1}{2} < |V_{cb}^R|, |V_{ts}^R| \le 1/\sqrt{2} \,. \end{gathered} \tag{8}$$

The somewhat smaller than standard model value of V_{cs}^R may increase the inclusive B semileptonic branching ratio by 10%. This is not intolerable when compared with experiment [2,8]. The neutral K mass difference, Δm_K, obtains new contributions from W_L, W_R box diagrams which are strongly enhanced [9]. Requiring that the two-c exchange contribution is not larger than the experimental value of ΔM_K implies [3]

$$\beta_g |V_{cs}^R V_{cd}^R| < 0.0005 \Longrightarrow |V_{cd}^R| < 0.01 \,. \tag{9}$$

All the other W_L, W_R box contributions from u and c exchange are sufficiently small. t-exchange amplitudes vanish.

From Eqs. (4)-(9) we find the following solution for a real orthogonal matrix V^R, written in terms of a single parameter:

$$V^R = \begin{pmatrix} c^2 & -cs & s \\ s(1-c)/\sqrt{2} & (c+s^2)/\sqrt{2} & c/\sqrt{2} \\ -s(1+c)/\sqrt{2} & -(c-s^2)/\sqrt{2} & c/\sqrt{2} \end{pmatrix}, \tag{10}$$

where $s=\sin\theta_1^R$, $c=\cos\theta_1^R$. There is maximal mixing between the second and third family ($\theta_{23}^R = 45°$), and a small mixing (θ_1^R) between these families and the first one. θ_1^R is determined from the measured value of $|V_{ub}/V_{cb}|$:

$$s \approx \tan\theta_1^R = \frac{1}{\sqrt{2}} \left| \frac{V_{ub}}{V_{cb}} \right| = 0.09 \pm 0.03 \,. \tag{11}$$

M_R^g is related to the value of $|V_{cb}|$:

$$M_R^g \approx \frac{M_L}{(2|V_{cb}|^2 - |\zeta_g|^2)^{1/4}} = 300\text{–}600\ \text{GeV} \,. \tag{12}$$

This range of values follows from the uncertainties in $|V_{cb}|, |\zeta_g|$.

A very crucial test of our model is the measured value of B_d^0-$\bar{B}_d^0$ mixing. This mixing is nicely explained within the standard model by the dominant contribution of the two-t-quark box diagram [10]. In our model this diagram is absent (as well as other two-W_L exchange diagrams which involve the t quark) since $V_{td}^L = 0$. The other two-W_L box diagrams, which involve the u and c quarks, are too small, as they are in the standard model. A new contribution from a box diagram with W_R exchange or from W_L-W_R mixing must therefore contribute with a suitable magnitude. Potential candidates are a two-W_R diagram with two-t exchange and a W_L, W_R box diagram with c and t exchange. All other terms are much smaller for a small mixing parameter $|\zeta_g|$. (For large mixing also the diagram with two W_L-W_R mixings and two t exchanges leads to a sizable contribution.) A straightforward calculation of these two contributions to B_d^0-$\bar{B}_d^0$ mixing gives the following results, respectively [10,11]:

$$\begin{aligned} x_d^{RR}(tt) &\approx \frac{G_F^2}{6\pi^2} \eta \tau_B M_B B_B f_B^2 m_t^2 \left(\frac{M_L}{M_R^g} \right)^4 s^2 = 0.03 \left(\frac{\tau_B}{1.2\ \text{ps}} \right) \left(\frac{B_B^{1/2} f_B}{0.15\ \text{GeV}} \right)^2 \left(\frac{m_t}{100\ \text{GeV}} \right)^2 \left(\frac{450\ \text{GeV}}{M_R^g} \right)^4 \left(\frac{s}{0.09} \right)^2, \\ x_d^{LR}(ct) &\approx \frac{G_F^2}{\pi^2} \eta_{ct}^{LR} \tau_B M_B B_B f_B^2 m_c M_L \left(\frac{M_L}{M_R^g} \right)^2 \sin\theta_C\, s F\left(\frac{m_t^2}{M_L^2}, \frac{M_L^2}{M_R^2} \right) \\ &= 0.32 \left(\frac{\tau_B}{1.2\ \text{ps}} \right) \left(\frac{B_B^{1/2} f_B}{0.15\ \text{GeV}} \right)^2 \left(\frac{450\ \text{GeV}}{M_R^g} \right)^2 \left(\frac{s}{0.09} \right) . \end{aligned} \tag{13}$$

We used the values $M_B=5.28$ GeV, $m_c=1.5$ GeV, $\eta=0.85$, $\eta_{ct}^{LR}=1$ [12], and $F=1.5$. [$F(x,\beta)$ depends very weakly on $x=m_t^2/M_L^2$, $\beta=M_L^2/M_R^2$ [11].]

Given the uncertainties in the values of $\tau_B=1.24 \pm 0.09$ ps [2], $B_B^{1/2} f_B=0.15 \pm 0.05$ GeV [10], $89 < m_t < 182$ GeV [13], M_R^g [Eq. (12)], and s [Eq. (11)], these two contributions account nicely for the observed B_d^0-$\bar{B}_d^0$ mixing, $x_d=0.66 \pm 0.11$ [2]. Thus, our model of right-handed b decays is well tested by its prediction of B_d^0-$\bar{B}_d^0$ mixing. B_s-$\bar{B}_s$ mixing is expected to be much larger, since the contributions $x_s^{RR}(tt)$, $x_s^{LR}(ct)$ contain enhancement factors of $(1/2s)^2$ and $1/2s \sin\theta_C$ relative to $x_d^{RR}(tt)$ and $x_d^{LR}(ct)$, respectively. This is quite similar to the standard model prediction [10].

To test our model against the measured CP violation in K decays requires introduction of phases in V^R, while V^L which mixes only the first two families can be chosen to be real. One may show that neither small phases in V^R nor a fine-tuned cancellation between a few contributions to ϵ are required [14] to account for the measured CP violation. Consider, for instance, the case $\zeta_g=0$ and add phases $-\phi,\phi,0$ to the elements of the first, second, and third rows of the matrix V^R, respectively. In this case an estimate based on the (u,c)-exchange W_L-W_R box diagrams [14] gives $|\epsilon| \sim 0.03 \sin 2\phi$. That is, the observed CP violation in the kaon system ($|\epsilon|=2.26\times 10^{-3}$) is accounted for by a sizable phase.

As mentioned above, our scheme requires a right-handed neutrino with $m(\nu_R) < m_b - m_c$. A reasonable upper limit for semileptonic B decays is $m(\nu_R) < 200$ MeV. For very light ν_R's, muon decay experiments [15] are already sensitive to the lower half range of Eq. (12), excluding in our model $M_R^g < 470$ GeV. In fact, the result of these experiments is 2.4σ away from $V-A$, favoring a value of M_R^g around 500 GeV [3]. We note that such a value requires $|\zeta_g|=0.035$–0.040 [16]. Another possibility is that of unstable massive right-handed neutrinos [$7 < m(\nu_R) < 200$ MeV] which avoid limits from muon decay. This allows values of M_R^g also in the lower half range of Eq. (12) and values of $|\zeta_g|$ which are much smaller than the above. Searches for secondary monoenergetic peaks in $\pi \to l\nu$, $K \to l\nu$ [17] leave the allowed ranges $140 < m(\nu_{eR}) < 200$ MeV and $35 < m(\nu_{\mu R}) < 70$ MeV. Experimental searches for decays downstream of accelerator neutrino sources [18] do not apply to our model. We neglect ν_L-ν_R mixing, assumed to be small, so that for $\zeta_g=0$ only the decay $\nu_{eR} \to e\mu\nu_{\mu R}$ can occur. This is forbidden for $m(\nu_{eR}) - m(\nu_{\mu R}) < m_\mu + m_e$. Neutrinos in the remaining mass range must decay invisibly [19] to evade the cosmological energy density constraint. In order to avoid a constraint from neutrinoless double-beta decay one may assume ν_{eR} to be a Dirac particle [3].

We made no specific assumption about the Higgs structure of the left-right model. Thus the mass of the extra Z' is not predictable and Z-Z' mixing can be assumed to be small to minimize Z' effects in $Z \to b\bar{b}$. When neglecting ν_L-ν_R mixing, neutrino counting by the measured Z invisible decay width is unaffected by ν_R.

At this point we come to the question of direct experimental tests of the left-handedness of b decay couplings. The most standard ways use semileptonic B decays. However, previously proposed tests cannot distinguish between the standard model and our model. In our scheme not only is the b-to-c (u) current right handed, but so is the associated lepton current in the W_R exchange amplitude. This amplitude may dominate over the W_L-W_R mixing amplitude. In this case measurements which depend on the product of the chiralities of quark and lepton couplings do not distinguish our model from purely left-handed couplings. Parity-violating observables are the only ones which test the chirality of the b-to-c coupling independent of the chirality of the lepton current.

To demonstrate our point, let us first discuss the inclusive lepton energy spectrum of B decays. It was noted by Altarelli *et al.* [20] that a slight deviation of this spectrum from the standard model expectation would arise if the b-to-c coupling were right handed. A $V-A$ lepton current was assumed. This deviation disappears in our model for $\zeta_g=0$ (and is presumably washed out by the hadron-model dependence anyway).

A more elaborate chirality test of the b-to-c coupling consists of measuring the decay distribution of $B \to D^*(\to D\pi)l\nu$. It was argued [21] that the sign of the forward-backward asymmetry of the lepton l with respect to the D^* in the $l\nu$ center-of-mass frame is determined by the chirality of the b-to-c coupling [22]. In fact, this asymmetry is not parity violating but rather of the type $\langle \bar{p}_l \cdot \bar{p}_{D^*} \rangle$. Since it is proportional to the chirality of the quark current [21], it must also be proportional to the chirality of the lepton current. Therefore, the sign of this asymmetry cannot distinguish the standard model from our model as long as the W_R exchange amplitude is larger than the W_L-W_R mixing amplitude.

It seems rather difficult to test the chirality of the b-to-c coupling independent of the associated chirality of the lepton current. The chirality of the c quark coupling was determined in dimuon production neutrino experiments [23]. b production cross sections in neutrino scattering experiments are too much suppressed by the tiny u-to-b coupling and by the low charm content in the nucleon [24]. Measurement of the τ (stopped μ) polarization in semileptonic B decays by the τ (μ) decay distribution could, in principle, measure the chirality of the associated lepton current.

In conclusion, we presented a version of an $SU(2)_L \times SU(2)_R \times U(1)$ model with purely right-handed b decay couplings, which satisfies all existing experimental constraints. The observed B decays, the measurement of B_d^0-$\bar{B}_d^0$ mixing, and CP violation in K decays are interpreted in our scheme as new right-handed physics. We focused our study on the structure of the left- and right-handed quark mixing matrices. The three CKM "mixing angles" of the standard model, $|V_{us}|$, $|V_{cb}|$, and $|V_{ub}|$, are replaced in our model by the three parameters θ_C,

$(\beta_g^2+|\zeta_g|^2)^{1/2}$, and s, respectively. In the model nonleptonic decay amplitudes induced by $b\rightarrow c\bar{c}s$ have an extra $1/\sqrt{2}$ suppression relative to the standard model and $b\rightarrow c\bar{c}d$ is highly suppressed. Theoretical and experimental uncertainties in nonleptonic decays such as $B\rightarrow K\psi$ and the theoretical uncertainty in the semileptonic branching ratio must be reduced to distinguish this model from the standard model. Certain previously proposed tests of $V-A$ in semileptonic B decays cannot make this distinction in principle when our associated lepton current has a dominant $V+A$ component. The mass of the right-handed gauge boson may be below 1 TeV. Direct searches for a second gauge boson at hadron colliders are therefore very important. Recent searches [25] have already obtained the limit $M_R>520$ GeV for $g_R=g_L$. We note, however, that M_R would be larger than M_R^g given by Eq. (12) if g_R were somewhat larger than g_L. Finally, even if our model were to fail some experimental test, it surely demonstrates certain loose aspects of B physics which must be tightened to put the standard model on yet a firmer ground.

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