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Flavor-changing neutral currents and rare *B* decays in 3-3-1 models

J.-Alexis Rodriguez*
Departmento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia

Marc Sher†
Particle Theory Group, Department of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA
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An interesting extension of the standard model is based on the electroweak gauge group $SU(3)_L \times U(1)$. It requires three generations to cancel anomalies, treats the third generation differently than the first two, and has a rich phenomenology. There are several models, distinguished by the embedding of the charge operator into the $SU(3)_L$ group and by the choice of fermion representations. In this brief report, we consider flavor-changing neutral currents in these models, concentrating on the $P - \overline{P}$ mass difference, where $P = (K, D, B, B_s)$, as well as $B \to K l^+ l^-$, $B \to \mu^+\mu^-$, and $B_s \to \mu^+\mu^-$ decays. Although the $P - \overline{P}$ mass difference has been considered previously in some models, the rare B decays are new. We find that the strongest bounds come from the $B - \overline{B}$ and $B_s - \overline{B}_s$ mass difference.

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I. INTRODUCTION

One of the more intriguing extensions of the standard model is based on the gauge group $SU(3)_c \times SU(3)_L \times U(1)$. In the original, minimal version of the model [1,2], the charged leptons and neutrinos are put into antitriplets of $SU(3)_L$, two generations of left-handed quarks are put into triplets, and the other generation into an antitriplet. This structure automatically cancels all anomalies, and when combined with the requirement of asymptotic freedom, necessitates that the number of generations is equal to three. The model has an automatic Peccei-Quinn symmetry [3,4]. The fact that one of the quark families is treated differently than the other two could lead to an explanation of the heavy top quark mass [5]. This minimal model contains doubly charged bilepton gauge fields, as well as isosinglet quarks with exotic charges, leading to a rich phenomenology [6]. A particularly exciting feature of this model is that there is an *upper* bound on the scale of $SU(3)_L$ breaking which is within range of the LHC. We will refer to this prototype model as model A. A simple alternative to this model [7] is to change the lepton structure by replacing the standard model conjugate leptons e_i^c with heavy leptons E_i^+ and adding e_i^c and E_i^- singlets. This will be referred to as model A′.

In another version of the model, with a different embedding of the charge operator into $SU(3)_L \times U(1)$, the charged lepton in the antitriplet is replaced by a right-handed neutrino [8,9]. In this version, the bileptons are singly charged or neutral. This model will be referred to as model B. Another model, model C, can be found [10] in which there are no lepton-number violating gauge bosons and no exotic quark charges (at the price of adding an isosinglet charged lepton for each generation). In all of these models, one still treats one of the quark generations differently than the other two. A very comprehensive review of the gauge, fermion, and scalar sectors of all of these models can be found in Refs. [11,12].

It is most natural to have the third generation be the "different" generation, since this might explain the heavy top quark and since some of the constraints to be discussed below are substantially weakened. With generations treated differently, one will expect to have tree-level flavor-changing neutral currents (FCNC). Thus, it is expected that FCNC involving the third generation will be dominant. Given the success of BELLE and *BABAR*, an analysis (and update of previous analyses) of rare B decays and FCNC in these models seems warranted. In this paper, we update bounds from the $P - \overline{P}$ mass difference, calculate new bounds from the $B_s - \overline{B}_s$ mass difference in models B and C, and determine the bounds from $B \to K f\bar{f}$ and $B \to f\bar{f}$ in all four models.

A nice discussion of FCNC interactions in the minimal model, model A, can be found in the works of Liu [13] and Gomez Dumm, *et al.* [14]. The interactions depend on undetermined mixing angles and the mass of the Z' boson. They calculated the $P - \overline{P}$ mass difference in this model. These results are over ten years old. Using updated experimental values for the mixing angles and bag constants, we find the bounds in the first column of Table I.

One can use these results, as done by Liu [13] to bound the mixing angles. Alternatively, one can assume a Fritzsch-like structure [14], and write (with $i \geq j$) $V_{ij} = \sqrt{m_j/m_i}$ (similarly for U_{ij}) and then find bounds on $m_{Z'}$. Doing so gives an upper bound on $m_{Z'}$, in TeV units, shown also in the first column of Table I. These bounds, especially for the $B - \overline{B}$ system, are very severe and are well in excess of model A's upper bound on the Z' mass. The angles must thus be smaller than one's naive expectation,

*Electronic address: jarodriguezl@unal.edu.co
†Electronic address: sher@physics.wm.edu

TABLE I. Bounds on the models described in the text from several flavor-changing neutral processes. The upper number is the bound on $|V^*_{3i}V_{3j}|\frac{m_Z}{m_{Z'}}$, where i and j refer to the relevant quark masses (and the V's are replaced by U's for Δm_D); for the rare B decays, the upper number is the bound on $|V^*_{3i}V_{3j}|^{1/2}\frac{m_Z}{m_{Z'}}$. The lower number is the lower bound on the Z' mass assuming a Fritzsch structure for the V matrix.

	Model A	Model A′	Model B	Model C
Δm_K	1.6×10^{-4}	1.6×10^{-4}	4.7×10^{-4}	1.7×10^{-4}
	4.8 TeV	4.8 TeV	1.7 TeV	4.5 TeV
Δm_D	1.6×10^{-4}	1.6×10^{-4}	4.8×10^{-4}	1.8×10^{-4}
	250 GeV	250 GeV	80 GeV	220 GeV
Δm_B	1.4×10^{-4}	1.4×10^{-4}	4.1×10^{-4}	1.5×10^{-4}
	30.7 TeV	30.7 TeV	10.5 TeV	28.2 TeV
Δm_{B_s}	1.1×10^{-3}	1.1×10^{-3}	3.3×10^{-3}	1.2×10^{-3}
	14.7 TeV	14.7 TeV	5.0 TeV	13.5 TeV
$B_{d,s}\to\mu^+\mu^-$	0.15	0.038	0.11	0.32
	230 GeV	1.0 TeV	340 GeV	121 GeV
$B\to K\mu^+\mu^-$	3.2×10^{-2}	9×10^{-3}	3.5×10^{-2}	4.6×10^{-2}
	1.2 TeV	4.3 TeV	1.1 TeV	800 GeV

or the model is excluded. It is also shown by Liu [13] and Gomez Dumm [14] that if one chose the first or second generation fields to be picked out as being different, then the bound would be much, much stronger—closer to 1000 TeV.

The success of the B factories has led to stringent bounds on $B\to Kf^+f^-$, $B\to f^+f^-$, and $B_s\to f^+f^-$. We now calculate these processes in this model.

For $B\to Kf^+f^-$, only the vector part of the interaction will contribute, and thus the matrix element $\langle K|\bar{s}\gamma^\mu b|B\rangle$ is needed. We use the matrix elements of Isgur, *et al.* [15], as discussed in Ref. [16], which gives a value of $2f_+p_K^\mu$, where f_+ is given by $\frac{3\sqrt{2}}{8}\sqrt{\frac{m_b}{m_q}}\exp(\frac{m_K-E_K}{m_K})$. Here, m_q is taken to be a constituent quark mass, or 300 MeV. Given this matrix element, the calculation is straightforward, and we find that the partial width is given, in GeV units, by $\Gamma = 1.7\times 10^{-15}V_{32}^2(\frac{M_Z}{M_{Z'}})^4$. Using the experimental bound and the Fritzsch ansatz, we find a bound of 1.2 TeV on the mass of the Z', as seen in Table I. This is substantially weaker than the bound from $B_s-\overline{B}_s$ mixing.

For $B_s\to f^+f^-$, only the axial vector part of the interaction contributes. Note that a helicity suppression makes the branching ratio proportional to the square of the final state fermion mass. The best experimental bounds are for muon final states ($B_s\to\tau^+\tau^-$ would be very interesting if one could come within a factor of a few hundred of the muonic branching ratio). The standard axial vector matrix element $\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B_s\rangle = f_{B_s}p^\mu$ is used, and we find that

$$\Gamma = \frac{G_F^2M_Z^4f_B^2V_{32}^2m_Bm_\mu^2}{36\pi M_{Z'}^4}. \quad (1)$$

Comparing with the experimental bound and using the Fritzsch ansatz gives a lower bound of 0.23 TeV on the Z' mass. For $B\to f^+f^-$, we find very similar numerical results. Again, this is substantially weaker than the bound from mixing.

It is important to note that even if one abandoned the Fritzsch ansatz (as one must for the model to be phenomenologically acceptable), the bound from quark-antiquark mixing will always be stronger [unless V_{32} is exceptionally small (less than 10^{-3}) in which case the bound on $m_{Z'}$ is less than the direct search bound]. In short, there can be *no substantial contribution* to these rare B decays in this model (since a substantial contribution would lead to an overly large contribution to $B-\overline{B}$ mixing), and this statement is independent of the mixing angles. It should also be noted that we have ignored contributions from Z exchange and from flavor-changing neutral Higgs exchange. These could destructively interfere, weakening the bounds. However, this would require some fine tuning and since the Higgs sector has many free parameters, we do not consider this possibility.

In model A′, the only difference is in the coupling of the final state leptons to the Z'. While the mass differences are unchanged, there are substantial changes in rare B decays. We find the bounds (see Table I) on $B\to K\mu^+\mu^-$ to be 4.3 TeV, and the bound from $B_s\to\mu^+\mu^-$ to be 1.0 TeV. Again, the bounds from the mass difference in the $B-\overline{B}$ system are stronger.

In model B, the mass differences in the neutral K, D, and B system (but not the B_s) were calculated in Ref. [17], and the bounds from the rare kaon decay $K^+\to\pi^+\nu\overline{\nu}$ were calculated [18]. We have reanalyzed these bounds, using updated constraints, and included the bounds from the B_s mass difference and the rare B and B_s decays discussed above.

Again, if one assumes a Fritzsch-type structure for the U and V matrices, lower bounds on the Z' mass are obtained (one can easily remove that assumption and present results in terms of, for example, the V_{ij} and quark masses). The calculation is the same as for model A, with different couplings. We find the bounds listed in the third column of Table I. Again, the bounds from the mass differences are much stronger than from rare B decays, and are weaker than for model A (primarily due to the absence of a $1-4\sin^2\theta_W$ factor).

In model C, the only calculation of flavor-changing neutral current effects that we are aware of is the calculation of the mass difference in the neutral kaon system by Ozer, in Ref. [10]. The fourth column of Table I lists all of the other bounds. The bounds from mass differences are substantially stronger than in model B.

II. CONCLUSIONS

$SU(3)_L\times U(1)$ models fall into two categories, depending on the embedding of the charge operator into the $SU(3)_L$ group. The choices of fermion representations further subdivides the models. These models all have tree-level FCNC mediated by gauge bosons. We have calculated the $P - \overline{P}$ mass differences and several rare B decays in these models. In all cases, we find that the contribution from rare B decays is much smaller than those from $B - \overline{B}$ and $B_s - \overline{B}_s$ mass differences, and thus the models predict that there should be no substantial contribution to these rare B decays (independent of mixing angles). Even though the bounds that we have found are somewhat weaker, they are still useful; the mass differences are much more sensitive to loop effects, and it is possible that there will be mild cancellations. Lower bounds on gauge boson masses are typically of the order of tens of TeV if one assumes a Fritzch-like structure for the mixing angles. This is a serious problem for the original, minimal model, which has an upper bound of approximately 2–3 TeV for the gauge boson masses. Thus, these models can only survive if the mixing angles are much smaller than one's naive expectation. This would mean that the down-quark mixing matrix would be very nearly diagonal, and thus Cabibbo-Kobayashi-Maskawa mixing would have to arise from the $Q = 2/3$ sector. This severely constrains attempts to understand the origin of flavor in these models.

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