Possibility of Discovering the Next Charge $-\frac{1}{3}$ Quark through Its Flavor-Changing Neutral-Current Decays

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If a fourth fermion generation exists, it is possible that the next charge $-\frac{1}{3}$ quark (b') is lighter than the top. The leading charged-current transition $b' \to cW^*$ is expected to be strongly suppressed by mixing angles. This leads to the interesting and likely consequence that the b'-quark decay is completely dominated by loop-induced flavor-changing neutral currents, which have distinctive experimental signatures. The relative importance of $b' \to bg^*$, $b' \to b\gamma$, and $b' \to bZ$ transitions (as well as comparisons with $b' \to cW^*$) are explored for b' masses up to 130 GeV.

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If a fourth generation exists, since t is as yet unseen, it may well be that $m_{b'} < m_t$.[1] Then, the leading charged-current (CC) decay is $b' \to cW^*$, where the W could be virtual or real. This rate is expected to be strongly suppressed by a small mixing $V_{cb'}$. The phenomenological consequences of this situation have been discussed previously.[1,2] It has also been noticed[2] that flavor-changing neutral-current (FCNC) b' decays could occur with a sizable rate. We follow up on this latter point, and assert that if this scenario (existence of a fourth generation and $m_{b'} < m_t$) is true, FCNC processes may dominate b'-quark decays.

The qualitative reasoning is as follows. As argued, one expects a decoupling of heavy-quark effects from low-energy physics, leading to small cross-generation mixing-matrix elements. This is quantitatively supported by $V_{ub} \ll V_{cb} \ll V_{tb}$. On the other hand, little is known about the mixing between the third- and fourth-generation quark doublets, while, especially if $m_{b'} < m_t$, this sector of the mixing matrix could be nontrivial. Thus, given the Cabibbo mixing between the first and second generations, the 4×4 mixing matrix is essentially block diagonal: the two diagonal 2×2 matrices being nontrivial (the new one to be determined by experiment), while the off-diagonal ones are close to zero, in line with decoupling. In this way one expects

$$V_{ub'} \ll V_{cb'} \ll V_{tb'}, \tag{1}$$

and $V_{ub'} \ll V_{ub}$, $V_{cb'} \ll V_{cb}$, whereas not much can be said about the relations between V_{tb}, $V_{tb'}$, $V_{t'b}$, and $V_{t'b'}$, except that this 2×2 matrix is more or less unitary by itself. For induced FCNC $b' \to b$ transitions, the mixing elements that matter are (ignoring CP phases) $v_i \equiv V_{ib}V_{ib'}$, $i = u,c,t,t'$. Clearly, v_u and v_c can be ignored, and so

$$v_t \cong -v_{t'}, \tag{2}$$

which remains unknown and may be large. From Eqs. (1) and (2), we see that although $b' \to b$ processes are suppressed by some loop factor, these loop-induced FCNC decays may actually dominate over $b' \to cW^*$. This kind of kinematical situation (dominant CC decay kinematically forbidden) could have been realized in nature in a more concrete case. Imagine a world with three generations and $m_c > m_b$ but everything else the same. Given our present knowledge that $V_{ub} \ll V_{cb} \ll V_{tb} \simeq 1$, FCNC $b \to s$ decays would be on the same level as CC $b \to u$ decays, the latter even vanishing in the limit that $V_{ub} \to 0$.

Taking $m_{b'} < m_t$, we assume that loop-induced FCNC decays dominate the b' width, and explore the consequences, viz., the relative importance of several types of induced FCNC. We then come back and explore the parameter space of $V_{cb'}$ vs $V_{t'b}V_{t'b'}$ for which our assumption holds true.

We study processes involving neutral vector bosons $V^0 = \gamma$, g, and Z^0. The case of H^0 is important but depends on more parameters and will be discussed elsewhere. Figure 1 illustrates the basic type of diagrams that induce these FCNC. The form factors to be calculated are of the general form[3]

$$J_\mu = \bar{q}[\gamma_\mu F_L L + (i\sigma_{\mu\nu}q_\nu/M_Z)F_{TR}R]Q, \tag{3}$$

but for γ and g, due to current conservation, it can be

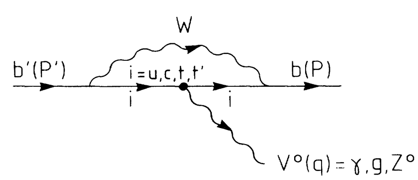

FIG. 1. A typical graph leading to an effective FCNC coupling.

rewritten as

$$J_\mu^{\gamma,g} = \bar{q}(q^2\gamma_\mu F_{1L}L + i\sigma_{\mu\nu}q_\nu m_Q F_{2R}R)Q\,, \qquad (4)$$

where F_{1L} and F_{2R} are simply related to usual definitions of form factors in the low-energy limit (vanishing external masses and momenta),[4] viz. F_1 and F_2, which we shall actually use in the following discussions. Ignoring v_u and v_c, from Eq. (2) one notices that the mixing-angle dependence is only on $v_{t'}$, which can be factorized, and the cancellation between t and t' contributions can be done at the numerical level. We use the algebraic manipulation package LERG-I,[5] written in REDUCE to express these form factors in terms of scalar one-loop integrals. LERG-I is a collection of procedures that follow and extend the work of Passarino and Veltman.[6] The three cases of $V^0=\gamma$, g, and Z^0 can be managed at the same time by a simple change of couplings that enter into our algebraic routine. Though our task is simplified by using LERG-I, expressions are still lengthy and cannot be published here. We employ the following three types of checks: (i) vector-current Ward identities; (ii) low-energy limit (we confirm many known results[4,7] in this limit, including the case with extra charged-Higgs-boson contributions); and (iii) numerical checks against the known nontrivial FCNC Z^0 decays.[8] More details of our computation, which is more general than the one applied here, will be given elsewhere.[9]

Passing these tests, we proceed to the numerical study of the case of interest. Aside from much more complicated form-factor evaluation, the situation for induced FCNC $b'\to b$ decays is similar to the $b\to s$ case, and we can learn from previous experience. For B mesons, $b\to sg^*$ occurs at the 1%–2% level,[7] although virtual gluon processes dominate and the final state typically involves $sq\bar{q}$ or sgg, i.e., three-body final states in terms of partons. There are also the interesting phenomena of large QCD corrections to $b\to s\gamma$.

Since the gluonic decay process is expected to dominate, it is important to check whether the $O(\alpha_s^2)$ three-body (three-jet) process ($b'\to bq\bar{q},bgg$) will dominate over the $O(\alpha_s)$ two-body (two-jet) process ($b'\to bg$). We find that this is not the case, and that in general F_1 is larger than F_2, but not much larger. In comparison, it is the large logarithm $[\ln(m_c^2/m_t^2)]$ picked up by F_1 but not by F_2 in the case of b that leads to the peculiar "higher-order dominance"; the charm contribution, however, is more or less decoupled from the $b'\to b$ transition, while $\ln(m_t^2/m_{t'}^2)$ is not very large. From similar arguments, and the fact that we are now at a scale comparable to the W mass, one does not expect QCD corrections to be very important.

There are two regions: (i) $m_{b'}<M_Z+m_b$, and (ii) $m_{b'}>M_Z+m_b$. For case (i), off-shell Z (and photon) contributions are an order of magnitude or more below the $b'\to b\gamma$ transition. In Fig. 2 we plot[10] the results for $b'\to b+$hadrons (the sum of $b'\to bg$ and $b'\to bg^*$) and

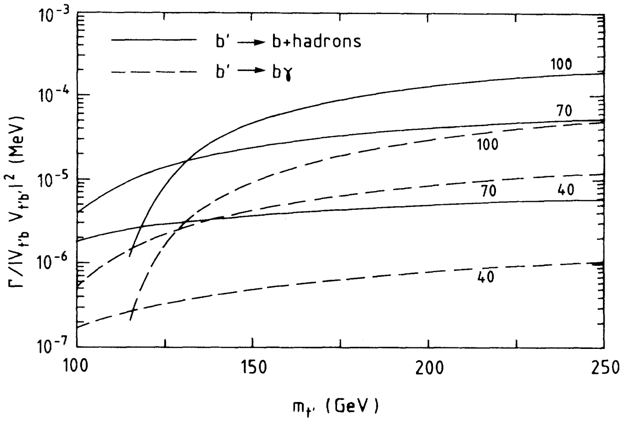

FIG. 2. Rates for $b'\to b+$hadrons and $b'\to b\gamma$ (with mixing coefficients factored out) vs $m_{t'}$ for $m_{b'}=40$, 70, and 100 GeV (as indicated). We take $m_t=m_{b'}+10$ GeV to maximize the FCNC rate.

$b'\to b\gamma$ versus $m_{t'}\in(100,250)$ GeV, for $m_{b'}=40$, 70, and 100 GeV. The hadronic FCNC b' decay is dominant. We have already commented that, closer to one's intuition, the lower-order (in α_s) two-jet final state $b'\to bg$ dominates over the higher-order three-jet $b'\to bg^*$ ($b'\to bq\bar{q}$, $q=u,d,s,c,b$, and $b'\to bgg$).[11] The fraction of $b'\to bg$ in the total $b'\to b+$hadrons is (for $m_{t'}=100$–250 GeV) (61–71)%, (75–82)%, and (85–88)%, respectively, for $m_{b'}=40$, 70, and 100 GeV, i.e., increasing as $m_{b'}$ or $m_{t'}$ increases. Similarly, the ratio of the photonic versus hadronic FCNC decay rate is (10–18)%, (13–23)%, and (17–26)%, with $m_{t'}$, $m_{b'}$ as above.

Let us try to understand these numbers. First, the suppression of the rates at low $m_{t'}$ reflects the Glashow-Iliopoulos-Maiani (GIM) mechanism, since t and t' contributions tend to cancel each other [see Eq. (2)], the more so when they are closer in mass.[10] Second, for larger $m_{t'}$, the curves are relatively flat. This reflects the fact that the $m_{t'}$ dependence of F_1 and F_2 at large $m_{t'}$ is at most logarithmic in nature. Third, we have already discussed the relative strength of three-jet versus two-jet hadronic FCNC decays. For the relative strength of the photonic versus the hadronic decays, a comparison between $b'\to b\gamma$ and $b'\to bg$ suffices, since the latter dominates the hadronic. One finds the ratio $\frac{3}{4}(\alpha/\alpha_s)\times(|\Delta F_2^\gamma|/|\Delta F_2^g|)^2$, where ΔF_2 is the difference between t and t' contributions. The large branching ratio (BR) into $b'\to b\gamma$ can be qualitatively understood in terms of a weaker α_s at the b' scale, and a relatively larger ΔF_2^γ vs ΔF_2^g. The latter is because γ can also be emitted from the virtual-W-boson line, which tends to dominate over Fig. 1 for large internal quark masses. In fact, $|\Delta F_2^\gamma/\Delta F_2^g|$ grows from roughly 2 to roughly 2.5–2.6 for the given $m_{t'}$ range, being larger for larger $m_{b'}$ values. This large BR into $b'\to b\gamma$ (direct photons) is a good handle for experimental studies.

For case (ii), on-shell $b' \to bZ$ decay dominates over $b' \to bg^*$ and $b' \to b\gamma$. We plot the results in Fig. 3, comparing only $b' \to bZ$ vs $b' \to bg$, since by far the latter is dominant compared to all the other $b' \to bZ$ processes, where qualitative features of the previous discussion remain. We illustrate with two $m_{b'}$ values, 100 and 130 GeV. For the former, one is just starting to have some phase space, whereas for the latter very heavy b' case, our hypothesis of $m_{b'} < m_t$ is losing its appeal, although having m_t, $m_{b'}$, and $m_{t'}$ all in the vicinity of a couple hundred GeV is an intriguing one. The $b' \to bZ$ process shares the GIM cancellation feature at low $m_{t'}$, but for larger $m_{t'}$, it grows strongly with $m_{t'}$. It is easy to understand why $b' \to bZ$ dominates over the other FCNC processes. For γ and g, current conservation demands that an explicit q^2 be factorized from $F_L^{\gamma,g}$. Thus, only the weaker F_{TR}, or F_2, contributes to $b' \to bg$ and $b' \to b\gamma$, whereas there is no such restriction for $b' \to bZ$. This also lends us the insight as to why F_L^Z has a much stronger $m_{t'}$ dependence ($\propto m_{t'}^2$ for large $m_{t'}$) as compared to the F_1 form factor for γ and g. The strong dependence of F_L^Z on m_Q is well known,[4,7,8] and is due to an effective strong (Yukawa) coupling, and coupling of longitudinal W's to heavy fermions; the decoupling theorem is thereby evaded. Numerically, $\Gamma(b' \to bg)/\Gamma(b' \to bZ)$ ranges between (77–8)% and (12–1)% for $m_{b'} = 100$ and 130 GeV, respectively, for $m_t \in (150,300)$ GeV (i.e., decreasing with $m_{t'}$).

We turn to discuss the parameter range for which our assumption of FCNC decay dominance is true. Ignoring $b' \to u$, our task is then basically to find the range of $r_{24} \equiv |V_{cb'}/V_{t'b}V_{t'b'}|$ for $\Gamma(b' \to cW^*) < \Gamma(b' \to b)$ to be true. There are three regions: (a) $m_{b'} < M_W + m_c$, (b) $M_W + m_c < m_{b'} < M_Z + m_b$, and (c) $m_{b'} > M_Z + m_b$. For (a), the W is virtual and decays into 9–10 channels (depending on the fourth generation lepton masses). For (b) b' can decay into on-shell W bosons, and the phase space becomes two-body, whereas, before region (c) is reached, FCNC decays involve only $b' \to bg^*$ and $b' \to b\gamma$.

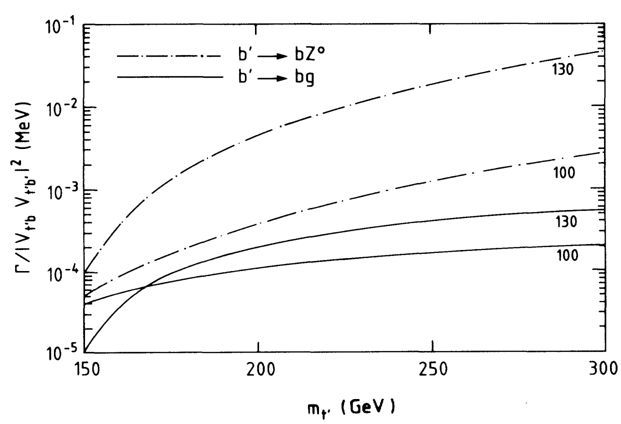

FIG. 3. Rates for $b' \to bg$ and $b' \to bZ$ (with mixing coefficients factored out) vs $m_{t'}$, for $m_{b'} = 100$ and 130 GeV (as indicated); $m_t = m_{b'} + 10$ GeV.

Computing and comparing the various CC and FCNC rates, we find that for FCNC to dominate the b' rate, we need $r_{24} \lesssim 10^{-2}$, 10^{-3}, and (10^{-3}–10^{-2}), for regions (a), (b), and (c), respectively. We have presented general values; they are smaller if one is in the strong GIM cancellation region (i.e., when $m_{t'}$ and m_t are close). A smooth matching between these mass regions would be achieved if one keeps the W and Z widths in the discussion.

The result is encouraging: For a large and natural range of parameter space, FCNC will indeed dominate over CC decays of b'. Compare with the analogous ratio $r_{13} \equiv |V_{ub}/V_{us}V_{ud}| \lesssim 3 \times 10^{-2}$. Both r_{24} and r_{13} are ratios of quark-mixing-matrix elements of two generation crossing over one generation crossing, with 3-4 and 1-2 generation elements as denominators, respectively. As argued earlier, these two 2×2 submatrices are the ones that could be nontrivial, whereas the off-diagonal 2×2 matrices should be close to zero. Given a general concept of decoupling, it is quite natural that r_{24} is smaller than r_{13}, and so $r_{24} < 10^{-2}$ should be naturally realized, whereas even 10^{-3} is not implausible. We conclude that if $m_{b'} < m_t$, FCNC decays would likely dominate over CC decays for b'. Only for $M_W + m_c < m_{b'} < M_Z + m_b$ will the CC decays have some chance of dominating. Another corollary is that if $m_{b'} > m_t$, so $b' \to tW^*$ is allowed with similar mixing coefficient ($V_{tb'}$) as the loop-induced FCNC, the latter would be at the level of 10^{-4} (unless $b' \to tW^*$ is phase-space suppressed), too small to be of immediate interest.

A brief discussion for search strategies following this scenario is called for. It should be noted that, already, there are limits of $m_t > 41$ GeV and $m_{b'} > 34$ GeV coming from the UA1 collaboration,[12] while limits from the cleaner e^+e^- environment of KEK are lower.[13] However, these limits come from explicitly or implicitly assuming usual charged-current decays of heavy flavors (isolated e/μ with jets). Although this should be the case for t, as has been argued, one has to be more cautious for the case of b'.

A careful reanalysis of data from the DESY and KEK e^+e^- colliders PETRA and TRISTAN should give us a reliable lower limit on $m_{b'}$. If $m_{b'} < 46$ GeV, b' quarks would be copiously produced at the CERN e^+e^- collider LEP, and one would find spectacular high-p_T four-jet events, forming roughly two back-to-back (in terms of p_T) pairs, each giving a mass peak (and Jacobian peaks in each of the jet p_T). Vertex detectors and other techniques can be used to identify a b quark in one jet, and perhaps indicate the other balancing jet as a gluon jet. Some fraction of the hadronic activity would be five-jet and six-jet events, with characteristics different from usual perturbative QCD effects. A very large fraction ($\gtrsim 20\%$) of the events would have one (or even two) of the "nonflavored" jets replaced by a direct, high-p_T photon, showing some Jacobian peak in p_T. All in all, discovery prospects at LEP should be excellent. Simultaneously, and for higher masses the only possibility (except for LEP II and future e^+e^+ machines), one can search for b' quarks through FCNC decays at hadronic facilities, looking for similar signals. The gluonic decays may still be distinguishable, although there is much more hadronic background; without a Monte Carlo simulation it is hard to tell. However, the large photonic FCNC BR should be a very useful handle. One should look for an excess of direct, isolated, high-p_T photons with associated energetic hadronic activity (three jets plus photon). For very heavy b' quarks, one has to inspect the Z^0 sample and see if there are any excesses (e.g., enhancement in Z^0-Z^0 pair production), and if there is any definite accompanying hadronic activity associated with the process $b' \rightarrow bZ$ ("isolated" e or μ *pairs* with jets). One should, of course, keep in mind that CC decays may also be present, and do a simultaneous study. In any rate, the possibilities are richer, and the current strategy of looking only for isolated leptons with accompanying jets should be broadened.

If $m_{b'} < m_t$ we may observe spectacular FCNC effects at high energy in the near future. The b' quark may predominantly decay via flavor-changing neutral currents: $b' \rightarrow bg^*$, $b' \rightarrow b\gamma$, and $b' \rightarrow bZ$. Present and future accelerators are excellent tools to study and check if this scenario is realized. Such studies may lead to fundamental new insights into the old problem of fermion masses and mixing patterns.

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[3]We set m_q to zero to simplify expressions, and so terms such as F_R and F_{TL} vanish. An additional q_μ term can be ignored since we consider on-shell V^0 or conserved-current final states. Similar discussions follow for Eq. (4).

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[7]For a short general discussion, and further references, see W. S. Hou, in Proceedings of the Twenty-Fourth International Conference on High Energy Physics, Munich, Germany, August 1988 (to be published).

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[9]W. S. Hou and R. G. Stuart, Max-Planck-Institut Report No. MPI-PAE PTh 55/88, 1988 (unpublished).

[10]We assume a nominal $m_t = m_{b'} + 10$ GeV to satisfy $m_{b'} < m_t$, and to allow for large FCNC rates. A larger m_t, i.e., closer to $m_{t'}$, would lead to smaller rates due to GIM cancellation between t and t'. $m_{t'}$ is made compatible with the usual ρ parameter and neutral-current constraints.

[11]We estimate $b' \rightarrow bgg$ rate by choosing a particular polarization sum for the two final gluons. Since $b' \rightarrow bg$ dominates, and $b' \rightarrow bq\bar{q}$ (which is gauge independent) is larger than $b' \rightarrow bgg$, the uncertainty involved is insignificant. A detailed calculation of $b' \rightarrow bgg$ demands the evaluation of four-point functions.

[12]M. J. Shochet, in Ref. 7.

[13]T. Kamae, in Ref. 7.