Decay of the b' Quark to a Standard Higgs Boson and a b Quark

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Attention is drawn to the fact that if the fourth family exists then the decay of the charge $-\frac{1}{3}$ member quark (b') may be a very rich source for production of the standard-model Higgs particle. While definitive numerical predictions are not possible at present since values of masses and mixings are unknown, we find that for $m_{b'} \lesssim 100$ GeV the mode $b' \rightarrow b+H$ can be a very important decay, if not the dominant decay, of the b'. Experimental consequences for hadronic and for e^+e^- colliders and strategies for the detection of this elusive particle are discussed.

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Despite the enormous successes of the standard model (SM) a crucial aspect of it remains unconfirmed, namely the Higgs particle.[1-3] Detection of this particle is a very important challenge and considerable effort is being devoted to that end. Indeed, a primary goal of the proposed Superconducting Super Collider is the search for this particle, as it is a vital link that is currently missing in our understanding of the electroweak theory.

While the standard model makes firm statements about the couplings of the Higgs particle to the gauge particles and to the fermions, it leaves the mass (m_H) of the Higgs particle completely unspecified. In fact, there are very few reliable constraints on m_H.[1-3] There is a lower bound of $m_H > 18$ MeV coming from nuclear physics.[4] Of more direct relevance for the current paper is a bound of $m_H \gtrsim 3$ GeV coming from B-meson decay, i.e., $B \rightarrow K+H$ (Ref. 5) or at the quark level $b \rightarrow s+H$, first discussed by Willey and Yu.[6]

The mechanism for Higgs-boson production that we want to consider is a generalization of the Willey-Yu mode to the corresponding case of the fourth family, namely $b' \rightarrow b+H$. For this process to be at all relevant it clearly requires the existence of the fourth family. While that is a drawback at the moment, we do believe that it is important to pursue the implications of the fourth family.[7] Indeed, in the past two years a considerable amount of work has been done in that direction. In passing we also note that Barger *et al.*[8] have already pointed out an interesting way to produce Higgs particles (in association with the Z^0) from decays of the bound states (i.e., quarkonia) of fourth-family quark-antiquark pairs. Our work complements theirs in that it deals with (weak) decays of flavored mesons such as B'_d, B'_s, and B'_u containing the b' quark.

The decay of interest $b' \rightarrow b+H$ takes place via the (generic) graphs of Fig. 1. While the process is related to $b \rightarrow s+H$, the calculation for our reaction $b' \rightarrow b+H$ is considerably more involved as neither the external nor the internal quark masses are ignorable. In contrast, in the calculation of $b \rightarrow s+H$ mode, the external b and s quark masses can be set to be zero in comparison to m_t and m_W. Thus considerable simplification is attained in that computation. In the decay $b' \rightarrow b+H$, $m_{b'}$, $m_{t'}$, m_W, and m_H all are important (i.e., nonignorable) masses in the problem. The expressions for the complete amplitude are therefore very tedious, are not illuminating, and will be published in a detailed article.[9] For the purpose of the present Letter we will discuss some special cases which should serve to illustrate the importance of this mode.

For convenience, discussion will be divided into three cases: (1) $m_{b'} < m_W$ and $m_{b'} < m_t$; (2) $m_{b'} < m_W$ and $m_{b'} > m_t$; and (3) $m_{b'} > m_W$. In the first case the dominant channel for the usual tree-graph decay via charge current is $b' \rightarrow c$, as $b' \rightarrow t$ is kinematically forbidden. This channel (i.e., $b' \rightarrow c$) leading to hadronic and semileptonic modes will be suppressed due to the expected smallness of the mixing angle $V_{b'c}$, in close analogy with V_{bu}. Indeed, empirical systematics of the mixing matrix[10] would suggest that the $b' \rightarrow c$ transition should be as severely suppressed as $b \rightarrow u$.[11] Thus one anticipates the branching ratios B for the effective flavor-changing neutral-current processes, in general, to be greatly

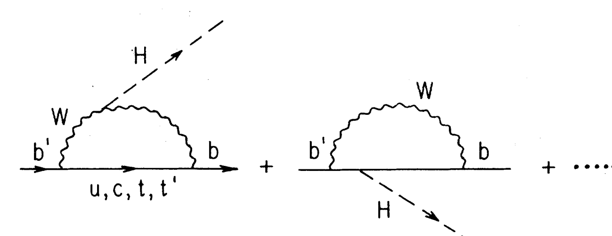

FIG. 1. Example of Feynman graphs for $b' \rightarrow b+H$. For a complete list, see Ref. 9.

enhanced over those for $b \to s$ (which in turn were enhanced over the $s \to d$ case).[11] The reaction $b' \to b+H$ under consideration (Fig. 1) is of course one such process.

To underscore the significance of this enhancement, let us, for example, consider $m_{b'}=70$ GeV and $m_{t'}=250$ GeV (with $m_{b'} > m_t$). Then one has the approximate result

$$\frac{B(b' \to Hb)}{B(b' \to ce\nu)} \simeq \frac{27\sqrt{2}}{64\pi^2} G_F \frac{m_{b'}^2}{f(m_q^2/m_{b'}^2)} \left(1 - \frac{m_H^2}{m_{b'}^2}\right)^2 \left|\frac{V_{bt}^\dagger V_{t'b'}}{V_{qb'}}\right|^2 \left(\frac{m_{t'}}{m_{b'}}\right)^4, \tag{1}$$

where $f(x)=1-8x+8x^3-x^4-12x^2\ln x$. For numerical illustration, taking[10] $|V_{bt'}/V_{b'c}|^2 \simeq (\theta^3/\theta^4)^2$ where θ is the Cabibbo angle, one finds[12]

$$\frac{\Gamma(b' \to Hb)}{\Gamma(b' \to ce\bar{\nu}_e)} \simeq \begin{cases} 3.9 \text{ for } m_H = 10 \text{ GeV}, \\ 1.0 \text{ for } m_H = 50 \text{ GeV}. \end{cases} \tag{2}$$

Thus we see that even for a moderately heavy Higgs boson flavor-changing neutral-current decay $b' \to bH$ can easily be comparable to the semileptonic branching ratio. Of course, for a light Higgs boson, it can completely dominate the semileptonic process.

Let us next consider the situation when $m_{b'} > m_t$. Then $b' \to t$ decays via charge current are kinematically allowed. Also one expects $V_{b't} \gg V_{b'c}$ and so semileptonic and hadronic decays of b' into t should be important. However, unless $m_{b'} \gg m_t$, the three-body phase-space suppression factor can now be severe. For illustration, let us again consider $m_{b'}=70$ GeV and take $m_t=50$ GeV. Then, although $|V_{t'b}/V_{tb'}|$ may be ~ 1, the phase-space suppression factor can be as much as 8×10^{-3}. Thus[12]

$$\frac{\Gamma(b' \to Hb)}{\Gamma(b' \to te\nu_e)+\Gamma(b' \to ce\nu)} = \begin{cases} 4.5 \text{ for } m_H = 10 \text{ GeV}, \\ 1.2 \text{ for } m_H = 50 \text{ GeV}, \end{cases} \tag{3}$$

so that the Higgs-boson mode can again be several times larger than the semileptonic one for a light (10 GeV) Higgs boson and may well still be comparable even for $m_H \sim 50$ GeV.

In Fig. 2 we show the numerical results (for $m_{b'} < m_W$) for various values of m_t as functions of m_H. Clearly for $m_{b'} < m_W$ the decays of b' into a Higgs boson

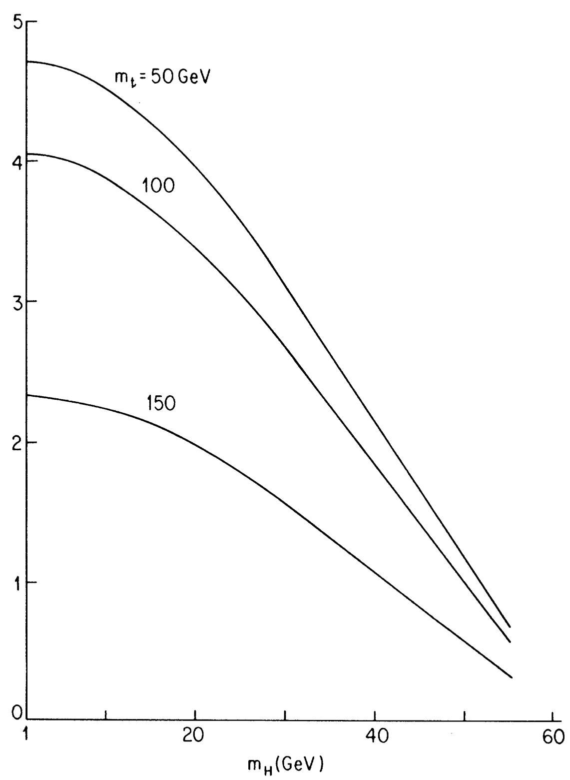

FIG. 2. $\Gamma(b' \to bH)/[\Gamma(b' \to ce\nu)+\Gamma(b' \to te\nu)]$ for $m_t=50$ GeV and $\Gamma(b' \to bH)/\Gamma(b' \to ce\nu)$ for $m_t=100$ and 150 GeV are shown as functions of m_H. $m_{b'}=70$ GeV and $m_{t'}=250$ GeV. See Ref. 12.

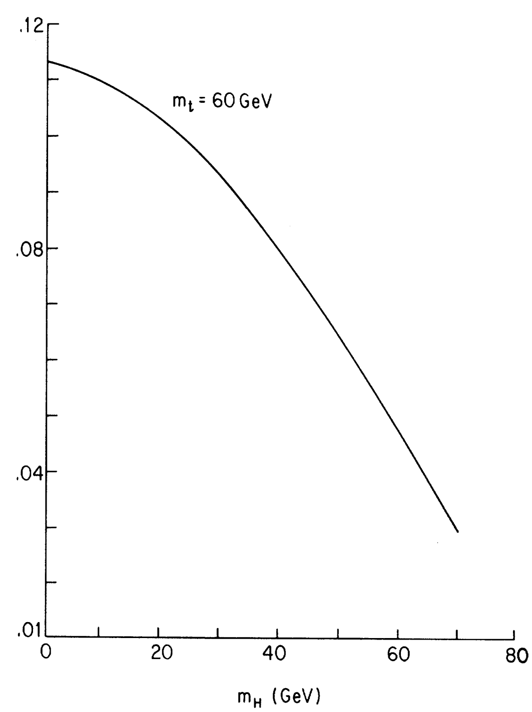

FIG. 3. $\Gamma(b' \to bH)/[\Gamma(b' \to Wc)B(W \to e\nu)+\Gamma(b' \to te\nu)]$ vs m_H is shown for $m_{b'}=100$ GeV, $m_t=60$ GeV and $m_{t'}=250$ GeV. See Ref. 12.

can be comparable to semileptonic branching ratios even for a reasonably heavy m_H. For example, for $m_{b'}=70$ GeV, the curves shown indicate that the Higgs-boson mode is larger than or equal to the electronic mode for $m_H \lesssim 40$ GeV.

When $m_{b'} > m_W$, then the two-body mode(s), $b' \to Wc(t)$, become very important. In Fig. 3 we illustrate this case for $m_{b'}=100$ GeV. Now the Higgs-boson mode is only about 10% of the inclusive electronic signal for $m_H \lesssim 10$ GeV and rapidly becomes uninteresting with increase in m_H. Indeed for $m_{b'}=200$ GeV, $B(b' \to b+H)$ becomes negligible.

A lack of knowledge of the relevant masses and mixings does not permit us to give precise numerical predictions for the branching ratio for $b' \to b+H$. However, the above special cases should serve to emphasize the potential importance of this process for the search for the standard Higgs particle if the parameters are favorable, especially if $m_{b'} \lesssim 100$ GeV. It is interesting also to note that the decay results in a b quark in the final state. This could prove crucial for experimental detection as vertex-detector techniques could be used to tag the b quark. Indeed for $m_H < 80$ GeV (actually for $m_H < 2m_t$ and/or $m_H < 2m_W$), $H \to b\bar{b}$ would have a substantial branching ratio. Thus $b' \to b+H$ followed by $H \to b\bar{b}$ could result in a distinctive final state of three b quarks with the invariant mass of a $b\bar{b}$ pair constrained to be the mass of H. The backgrounds in the environment of a hadron collider will be substantial but might be overcome with efficient tagging of B mesons.

At the CERN e^+e^- collider LEP II or a high-energy linear e^+e^- collider both the b' signal and the backgrounds would be significantly reduced. A more detailed study is required to assess the feasibility of finding the Higgs boson in this fashion.

In summary, if a fourth family exists and the b' is not too heavy compared to the W boson, the decay b' to $b+$Higgs boson has a significant branching ratio. The detection of the Higgs boson through this mechanism depends crucially on the ability to identify the subsequent decay of the Higgs boson to $b\bar{b}$.

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