Decays of B Mesons to Kaons without Charm and the Top-Quark Mass

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Decays of B mesons to kaons without charmed particles are shown to be sensitive to the top-quark mass, and therefore can be used to determine m_t or at least to set limits on it. For $m_t \simeq 2M_W$ the inclusive branching ratio is about 2%, while for $m_t \simeq 20$ GeV it is only 0.4%. The flavor-changing transition $b \rightarrow s$ + gluon is calculated and added to the penguin and the direct decay ($b \rightarrow u\bar{u}s$) contributions.

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By now it is known that m_t, the mass of the top quark, if it exists, is larger than[1] 18.35 GeV, since no $t\bar{t}$ states were found in e^+e^- collisions up to center-of-mass energies of 36.7 GeV. Is it possible to find m_t, or at least set limits on it, by means other than direct production[2] of top quarks? It was suggested[3] that neutral flavor-changing K decays (i.e., $s \rightarrow d$) are sensitive to the mass of virtual t quarks running in loops. However, this result is subject to uncertainties due to long-distance phenomena affecting kaon decays.

Decays of B mesons are expected to suffer less from theoretical uncertainties than K decays, since $m_b \gg m_s$. Indeed it was shown[4] that radiative b decays, $b \rightarrow s + \gamma$, are sensitive to m_t and for $m_t \gtrsim M_W$ the branching ratio is about 0.01%, while it drops by approximately a factor of 100 when $m_t \simeq 20$ GeV. I suggest here the consideration of flavor-changing neutral transitions (i.e., $b \rightarrow s$) without photons as a probe for the top-quark mass. These transitions will result in final states containing strange quarks which do not originate from charmed quarks. A branching ratio of more than 1% is found for these transitions if $m_t \gtrsim M_W$, dropping by about a factor of 3 when $m_t \simeq 20$ GeV. This result is a sum of the process $b \rightarrow s + g$, where g stands for a gluon (see Fig. 1), which is calculated here, and of the penguin-type process $b\bar{q} \rightarrow s\bar{q}$ for which we follow the calculation of Ref. 5. Both of these processes are absent in a world without gluons, and their mere existence is therefore a signature for strong corrections to weak decays of mesons, which cannot be directly measured in K and D decays but only in B decays.[5] For low values of m_t the direct decay[6] $b \rightarrow u\bar{u}s$, which is doubly Cabibbo suppressed, plays a role but it is of course independent of the top-quark mass. At the end of this Letter I will briefly discuss the difficulties involved in measuring kaons without charmed particles, the possibility of separating the two flavor-changing neutral processes discussed here, and the (remote) possibility of observing CP nonconservation in charged B decays. I will limit myself to the "standard model"[7] and will not discuss the effects of horizontal interactions or of flavor-changing neutral Higgs mesons.

The first process that I consider is[8] $b \rightarrow s + g$. The diagrams contributing to it are depicted in Fig. 1, where φ denotes the unphysical scalar which in all gauges—other than the unitary gauge—should be added,[9] unless[10] $m_t \ll M_W$. Then the width is

$$\Gamma(b \rightarrow s + g) = \frac{\alpha_s G_F^2 m_b^5}{32\pi^4} \left|\sum_i V_{is} V_{ib}^* F_i\right|^2, \tag{1}$$

where α_s is the strong-coupling constant, V_{kl} are the Kobayashi-Maskawa[11] (KM) mixing angles, and the sum extends over the intermediate quarks $i = u, c, t$. F_i is given by

$$F_i = \left[-\frac{1}{4}\frac{1}{x_i - 1} + \frac{3}{4}\frac{1}{(x_i - 1)^2} + \frac{3}{2}\frac{1}{(x_i - 1)^3}\right] x_i - \frac{3}{2}\frac{x_i^2}{(x_i - 1)^4}\ln x_i, \tag{2}$$

where $x_i = m_i^2/M_W^2$. For m_t larger than the current lower limit, the u and c contributions are much smaller than the t contribution. By looking at the KM matrix[12] it is clear that $(b \rightarrow s + g) \gg (b \rightarrow d + g)$, and thus the latter process will not be further discussed. To cancel wave-function uncertainties the following ratio R is calculated:

$$R = \frac{\Gamma(B \rightarrow g + X)}{\Gamma(B \rightarrow e + X)} = \frac{\Gamma(b \rightarrow g + s)}{\Gamma(b \rightarrow e + \nu + c) + \Gamma(b \rightarrow e + \nu + u)}. \tag{3}$$

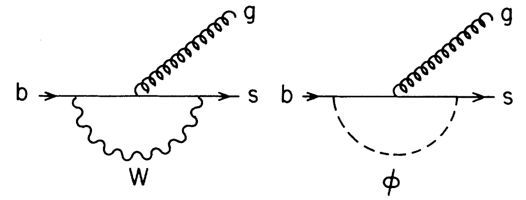

FIG. 1. Diagrams contributing to $b \to s + g$, in the 't Hooft–Feynman gauge with on-shell renormalization. g and φ denote a gluon and an unphysical scalar, respectively.

Therefore

$$R = \frac{6\alpha_s}{\pi} \frac{|\sum_i V_{is} V_{ib}{}^* F_i|^2}{|V_{bu}|^2 + |V_{bc}|^2 f(m_c{}^2/m_b{}^2)}, \tag{4}$$

where

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x. \tag{5}$$

I take $m_c = 1.5$ GeV, $m_b = 4.5$ GeV, $\alpha_s = 0.24$ (corresponding to $\Lambda = 200$ MeV), and[13] $B(B \to e + X) = 0.136$. In the short-dashed line in Fig. 2, the results for the branching ratio are presented for the following central values of the sines of the KM angles[12]: $s_1 = 0.228$, $s_2 = 0.1$, $s_3 = 0.3$, and $s_\delta = 0.03$ ($\delta \simeq 0$). The branching ratio is not too sensitive to changes in the angles, within the allowed values.[14] We see that the branching ratio for $B \to g + X$, where X has to include an s quark, depends strongly on m_t with values reaching 0.5% for large m_t. These branching ratios are about a factor of 30 larger than the corresponding values for[4] $B \to \gamma + X$.

The process $b \to s + g$ leads to final states with kaons, but without charmed particles. It is not the only process leading to such final states. The obvious one to consider is the doubly Cabibbo suppressed decay $b \to u\bar{u}s$. If we calculate this spectator decay and add the appropriate strong interaction correction factors, then[6]

$$\frac{\Gamma(b \to u\bar{u}s)}{\Gamma(b \to \text{all})} = \frac{0.19y}{7.69y + 3.07}, \tag{6}$$

where $y = |V_{bu}|^2/|V_{bc}|^2$. This ratio depends of course on the values of the KM angles, but is independent of m_t. In the horizontal line (long-dashed curve) in Fig. 2 the branching ratio for $B \to K + X$ which results from $b \to u\bar{u}s$ is plotted for the central values of the KM angles given above.

The third quark process contributing to B decays into kaons without charmed particles is the penguin process[5] $b\bar{q} \to s\bar{q}$. This contribution has u, c, and t quarks in the loop and gluons exchanged between the quarks in the loop and the $\bar{q}$ in the B meson. This process is similar to $s\bar{q} \to d\bar{q}$ which was invoked in order to explain the $\Delta I = \frac{1}{2}$ rule for K decay.[15] I use here the calculation of Guberina,[5] who studied this process using the renormalization-group equations to sum up leading logarithms, to all orders in quantum chromodynamics (QCD), but did not consider the dependence on m_t. In the dash-dotted line in Fig. 2 I plot the contribution of $b\bar{q} \to s\bar{q}$ to B decays using the same values for the angles as above (the results are not sensitive to this choice), $\Lambda = 200$ MeV, and $\mu = 4.5$ GeV (μ is the scale of QCD relevant for the problem, which is taken as m_b). This contribution increases by a factor of approximately 4.5 from $m_t/M_W = 0.3$ to $m_t/M_W \simeq 2$, and the ratio between the two QCD processes $b\bar{q} \to s\bar{q}$ and $b \to s + g$ decreases from about 30 at $m_t/M_W = 0.3$ to 3 for $m_t/M_W \simeq 2$.

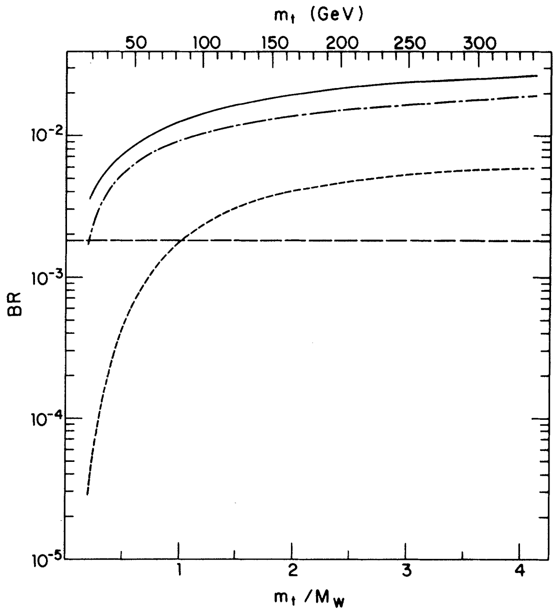

FIG. 2. Branching ratio for the inclusive decay $B \to K + X$ without charmed particles (solid line), as a function of the top-quark mass. This branching ratio is a sum of the following quark processes: the doubly Cabibbo suppressed decay (Ref. 6) $b \to u\bar{u}s$ (horizontal long-dashed line), the decay $b \to sg$ calculated here (short-dashed line), and the penguin contribution (Ref. 5) $b\bar{q} \to s\bar{q}$ (dash-dotted line). Sines of the KM angles used here are $s_1 = 0.228$, $s_2 = 0.1$, $s_3 = 0.3$, and $s_\delta = 0.03$ ($\delta \simeq 0$).

By adding the three quark processes discussed above, I obtain the total branching ratio for $B \to K + X$ without charmed particles, which is depicted by the solid line in Fig. 2. For $m_t \gtrsim M_W$,

$B(B \to K + X)$ reaches 1% and then keeps increasing as a function of m_t.

It is not easy to measure the inclusive decay rate of B mesons to kaons without charmed particles. Let me point out a few possible ways to achieve this goal.

(1) There should be an excess of kaons in nonleptonic decays as compared with semileptonic decays of B mesons, since the processes discussed here contribute to nonleptonic decays only. An improvement in the measurements of the number of kaons per event is therefore necessary.

(2) Both $b \to s + g$ and $b\bar{q} + s\bar{q}$ should lead to two jets, with a gluon recoiling against an s quark in the first case, and a quark recoiling against the s quark in the second case. Around 5 GeV a two-jet structure is apparent in e^+e^- collisions, and therefore the separation of the outgoing hadrons into two jets versus three jets from the dominant decay $b \to c\bar{u}d$ is in principle possible. If methods to distinguish gluon jets from quark jets are refined, it will be possible to separate $b \to s + g$ from $b\bar{q} \to s\bar{q}$. There is no need for such a separation to set limits on m_t since, as is clear from Fig. 2, both $bq \to s\bar{q}$ and $b \to s + g$ and thus their sum increase with m_t.

(3) The kaons coming from direct $B \to K + X$ transitions will have different energy and momentum distributions from those from $B \to D + X$ followed by $D \to K + X$. A quantitative calculation using a reasonable hadronization model and the necessary experimental cuts should be first performed to test the feasibility of the approach.

(4) There are final states such as $B_u \to \varphi K^- \pi^0$, which can result only from the direct $b \to s$ transition.[5]

(5) Whole events may be reconstructed, and all $K + n\pi$ masses around the D meson mass can be excluded.

(6) Vertex detectors may be able to distinguish decays of B mesons to kaons without charm, which involve a single "break," versus decays going through charm which will show two "breaks."

A most exciting possibility, though it seems rather remote at present, is to observe CP nonconservation in charged B decays. Until now CP nonconservation has been confined to the neutral K system. CP nonconservation in charged systems will manifest itself as different partial widths for a particle and its antiparticle. The processes discussed here involve loops and can therefore lead to such effects,[8] which will show, for instance, in $\Gamma(B_u \to K^- + X) \neq \Gamma(\bar{B}_u \to K^+ + X)$.

Let me emphasize that there are uncertainties in the estimates due mainly to the transition between the parton level and hadrons. In fact, the importance of similar effects has not been clearly established for strange and charmed particles; it is hoped that the B system is more suitable than lower-lying systems.

To summarize, pure QCD effects which are absent in the absence of gluon corrections to nonleptonic decays lead to a significant branching ratio for B decays to kaons without charmed particles. This branching ratio is sensitive to the top-quark mass and can therefore be employed to determine, or at least set limits on, m_t.

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[1] H. J. Behrend *et al.*, DESY Report No. DESY 81/209 (unpublished).

[2] In principle one can also look at the production of single top quarks in e^+e^- collisions, e.g., $e^+e^- \to t\bar{c}$ [see G. Eilam and N. G. Deshpande, University of Oregon Report No. OITS-169 (to be published), and G. Eilam, in Proceedings of the Moriond Workshop on Heavy Flavors, January 1982 (to be published)], but the cross section in the standard model is too small to be measured. The existence of flavor-changing Higgs mesons can of course change the situation [see D. R. T. Jones, G. L. Kane, and J. P. Leveille, Nucl. Phys. B198, 45 (1982)], and experimentalists are urged to look for this channel.

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[13] P. Franzini, in Proceedings of the Moriond Workshop on Heavy Flavors, January 1982 (to be published). The value quoted there is $B(B \rightarrow e+X)=0.136 \pm 0.025 \pm 0.03$. These errors result of course in errors for $B(B \rightarrow g+X)$ which are not shown in Fig. 2.

[14] If the angles are changed along the allowed lines in the s_2-s_3 plane (see Pakvasa, Tuan, and Sakurai, Ref. 12) then for $\delta \simeq 0$, $B(B \rightarrow g+X)$ changes by about 35%, while for $\delta \simeq \pi$ it changes by approximately 25%. For a fixed value of the angles, changing δ from $\delta=0$ to $\delta=\pi$ leads to a very small change in the branching ratio.

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