$B^0 \to D^{0*} + \gamma$ decay as a probe for short-distance QCD corrections

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We argue that, barring a large $gq\bar{q}$ component in the B^0 or D^{0*} meson wave functions, the $B^0 \to D^{0*} + \gamma$ decay will be highly suppressed by QCD short-distance corrections. This decay proceeds mainly through flavor annihilation, and "color thaw" by gluon emission from the initial quark legs is not expected to be operative here. Thus the relevant color suppression factor $A_{\rm QCD} = (2C_+ - C_-)^2 \lesssim 0.1$ should be in place. We calculate the decay rate in a nonrelativistic approximation and obtain the estimate $B(B^0 \to D^{0*} + \gamma) \approx 2 \times 10^{-6}$.

There are strong phenomenological indications that flavor annihilation (via W exchange) is important in many decays of neutral pseudoscalar mesons [e.g., $\tau_{D^+}/\tau_{D^-} \simeq 2.5$ (Ref. 1); $B(D^0 \to \bar{K}^0 \phi) \gtrsim 1\%$ (Ref. 2)]. On the other hand, the naive theoretical expectation is that these contributions are highly suppressed due to helicity effects and short-distance color corrections to the weak vertex.[3]

Two possible mechanisms to avoid this strong suppression have received much attention. One of these is based on the assumption that the decaying pseudoscalar meson has a large $q\bar{q}g$ component in its wave function.[4] Then the $q\bar{q}$ can be in a spin-1, color-octet state, thus overcoming both helicity and color suppression. The other mechanism, which seems more plausible to us, is the emission of gluons from the initial-quark legs (see Fig. 1).[5] Again, both helicity and color suppression are avoided and no special dynamical assumptions about the meson wave function are necessary. Whichever enhancement mechanism is operational, it should be present in most processes involving the flavor annihilation of neutral pseudoscalar mesons so that the naive helicity and color suppression is usually unobservable.

The best way of testing the above ideas is to find a decay that proceeds mainly through flavor annihilation and for which the color suppression is or is not in place depending on which mechanism is responsible for the usual enhancement ("color thaw"). We believe that the decay $B^0 \to D^{0*} + \gamma$ satisfies these requirements. It proceeds mostly through flavor annihilation (see Fig. 2) [$B^0 \to (D^+\pi^-) + \gamma \to D^{0*} + \gamma$ is very unlikely due to phase-space considerations]. Moreover, because of the photon emission there is no helicity suppression. Now, if the usual color thaw is due to the presence of valence glue in the wave function of the mesons (i.e., if B^0 or D^{0*} have an important $q\bar{q}g$ component), then the same mechanism should also be operational for the $B^0 \to D^{0*} + \gamma$ decay. This is because a valence gluon originating from one of the mesons may be attached to the quark legs of the other meson so that the weak transition is effectively octet$\to$octet instead of singlet$\to$singlet. Consequently the decay $B^0 \to D^{0*} + \gamma$ would be unsuppressed. On the other hand, if gluon emission from the initial quark legs is the usual color enhancement mechanism (which we think is more likely to be the case), it is not expected to operate in the decay $B^0 \to D^{0*} + \gamma$. The reason is that for this process the gluon(s) emitted from the initial quarks can only be reabsorbed by one of the four quark legs involved in the weak interaction. Therefore these gluons are just part of the usual QCD radiative corrections [$O(\alpha_s)$], which are superimposed on the short-distance color corrections. We then expect the short-distance suppression to remain in place.

We now estimate these effects quantitatively. The naive short-distance color suppression factor for the process $B^0 \to D^{0*} + \gamma$ (see Fig. 2) is given, in standard notation,[3] by

$$A_{\rm QCD} = (2C_+ - C_-)^2 \ . \tag{1}$$

The coefficients C_+, C_- of the effective weak Hamiltonian are calculated using renormalization-group methods. To next-to-leading-logarithm order, at a scale $\mu = 5$ GeV$\simeq M_B$ they are given by[3] $C_- = 1.4, 1.5$; $C_+ = (C_-)^{-1/2}$ for $\Lambda_{\overline{\rm MS}} = 0.2, 0.5$ GeV respectively ($\overline{\rm MS}$ denotes the modified minimal-subtraction scheme). The corresponding values for the color suppression factor are then [see Eq. (1)] $A_{\rm QCD} = 0.084, 0.017$. Although this factor is clearly sensitive to $\Lambda_{\overline{\rm MS}}$, we see that $A_{\rm QCD} < 0.1$ for reasonable values of $\Lambda_{\overline{\rm MS}}$ (Ref. 6). Thus, if $A_{\rm QCD}$ adequately describes the short-distance color effects of the

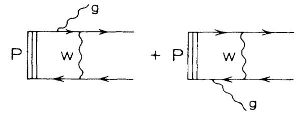

FIG. 1. Color and helicity enhancement due to gluon emission from the initial quark legs in neutral-pseduoscalar decay.

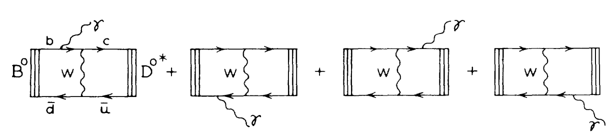

FIG. 2. Diagrams contributing to the decay $B^0 \to D^{0*} + \gamma$.

process $B^0 \to D^{0*} + \gamma$ (as we expect from the above discussion), the decay rate should be suppressed by a factor 10–50. Therefore the rate $\Gamma(B^0 \to D^{0*} + \gamma)$ should be useful to discriminate among different mechanisms of "color thaw."[7]

We now present an estimate for the rate $\Gamma(B^0 \to D^{0*} + \gamma)$ using the diagrams of Fig. 2 and a nonrelativistic approximation for the B and D^* meson wave functions. We make use of the invariant squared amplitude for the process $B^0 \to c + \bar{u} + \gamma$ [given in Eqs. (5)–(7) of Ref. 8], and then impose the kinematical restrictions on the c and $\bar{u}$ quarks to make up the D^{0*} meson. We obtain, assuming that the short-distance QCD suppression is operative, the result

$$\Gamma(B^0 \to D^{0*} + \gamma) = \tfrac{1}{36}\alpha G_F{}^2 M_{D^*}{}^2 f_B{}^2 f_{D^*}{}^2 E_\gamma \, | V_{du} V_{bc} |^2 (2C_+ - C_-)^2 \times \left[Q_b{}^2 \left[\frac{1}{m_b{}^2} + \frac{1}{m_d{}^2} \right] + Q_c{}^2 \left[\frac{M_{D^*}{}^2}{M_B{}^2} \right] \left[\frac{1}{m_c{}^2} + \frac{1}{m_u{}^2} \right] + 2Q_b Q_c \left[\frac{M_{D^*}}{M_B} \right] \left[\frac{1}{m_d m_c} + \frac{1}{m_b m_u} \right] \right], \quad (2)$$

where V_{ij} are the usual flavor-mixing-matrix elements, $f_B{}^2 \equiv (12/M_B) | \psi_B(0) |^2$, $f_{D^*}{}^2 \equiv (12/M_{D^*}) | \psi_{D^*}(0) |^2$ in the standard way; $Q_b = -\frac{1}{3}$ and $Q_c = \frac{2}{3}$ are the quark electric charges and m_i are the quark "constituent" masses. Although a nonrelativistic approximation for the B and D^* wave functions cannot be expected to give accurate results, we think that if constituent-quark masses are used and the values for f_B and f_{D^*} are taken from experiment (or from more realistic models), then Eq. (2) should be reliable to within a factor of 2. Setting $| V_{bc} | = 0.06$, $| V_{du} | = 0.97$ (Ref. 2); $f_B = f_{D^*} = 0.3$ GeV (Ref. 9) ($f_\pi \simeq 0.132$ GeV); $m_u = m_d \approx 0.3$ GeV, $m_c \approx 1.7$ GeV, $m_b \approx 4.97$ GeV; and $C_- = 1.4$, $C_+ = 0.84$ (corresponding to $\Lambda_{\overline{\rm MS}} = 0.2$ GeV) (Ref. 3), Eq. (2) gives

$$\Gamma(B^0 \to D^{0*} + \gamma) = 2 \times 10^{-19} \text{ GeV} . \quad (3)$$

If we assume $\tau_{B^0} \simeq 1.4$ ps (Ref. 2), this translates into a branching ratio

$$B(B^0 \to D^{0*} + \gamma) \simeq 2 \times 10^{-6} . \quad (4)$$

On the other hand, if the short-distance color suppression were not operative [i.e., if $(2C_+ - C_-)^2$ were replaced by $O(1)$], the expected branching ratio would be a factor of order 10 larger.

If the experimental branching ratio turns out to be of order 10^{-6} or smaller (and allowing for the obvious corrections to our estimate if $| V_{bc} |$, f_B, f_{D^*}, $\Lambda_{\overline{\rm MS}}$, or τ_{B^0} are very different from the values we assumed above) we will gain two pieces of information. One is that the short-distance color corrections to the weak vertex can strongly affect some physical processes; i.e., they are observable. The other is that the mechanism to overcome this suppression in inclusive decays is likely to be gluon emission from the initial legs.[8]

Although the expected branching ratio $B(B^0 \to D^{0*} + \gamma) \approx 10^{-6} - 10^{-5}$ is certainly small, it should be measurable once enough B^0's are produced, thanks to the nearly monochromatic 2.25-GeV photon and the clear signature of the decay $D^{0*} \to D\pi$.

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