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THE ROLE OF NONSPECTATOR INTERACTIONS IN CHARM AND BOTTOM DECAYS *

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ABSTRACT

The role of annihilation and exchange diagrams in charmed meson, Λ_c^+ and B meson decays is analyzed.

I. INTRODUCTION

Recent measurements[1] of charmed particle lifetimes and semileptonic branching fractions have made it necessary to revise our theoretical description of heavy particle decays. The conventional quark model for these decays assumes that the heavy quark decays freely with light quark constituents acting merely as spectators. This spectator model predicts equal lifetimes and semileptonic branching ratios for Λ_c^+ and the charmed mesons D^o, D^+, F^+, whereas recent data indicate that $\tau(D^+)/\tau(D^o) \sim \tau(D^+)/\tau(\Lambda_c^+) \sim 10$, $\tau(D^+)/\tau(F^+) \sim 5$, and $B(D^+ \to eX)/B(D^o \to eX)$ of order 3 or larger. Although preliminary, the data strongly suggest that D^o, F^+ and Λ_c^+ are shorter-lived than the D^+.

Additional contributions to the decay rates have been known for some time. These are of the nonspectator type, e.g., $c\bar{u} \to s\bar{d}$ in the case of the D^o. However, these contributions vanish in the Born approximation with vanishing light quark masses, $\Gamma(\text{nonspectator})/\Gamma(\text{spectator}) \sim m_s^2|\psi(0)|^2/m_D^5$ where $|\psi(0)|^2$ is the probability of finding the two constituent quarks at the origin. This vanishing of lowest order annihilation and exchange contributions with light quark masses is due to helicity suppression. It is analogous to the suppression of $\pi^- \to e^-\bar{\nu}_e$. In the rest frame of the decaying 0^- meson the outgoing quark and antiquark are collinear, so their spins must be antiparallel. Hence they must be either both right-handed or both left-handed. Since V-A theory wants a left-handed quark and a right-handed antiquark at the production vertex, chirality must be flipped at the cost of a power of a light quark mass in the amplitude.

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It was recently realized[2] that helicity suppression could be avoided in nonleptonic decays. A hard gluon can be radiated perturbatively from the light quark prior to the interaction allowing the quark-antiquark pair to interact in a spin-one state. Alternatively, a gluon may be present in the D^0 wavefunction. In the following we shall only consider the perturbative radiation of a gluon and refer to it as the <u>one-gluon model</u>. As we will show in the sequel, this model is in fair agreement with lifetimes and decay patterns observed experimentally. Most of our predictions, however, transcend the one-gluon model and remain valid provided <u>some</u> mechanism enhances nonspectator contributions.

For convenience we summarize our results here:

(i) We find a substantial enhancement for the Λ_c^+ decay rate from the interaction between the c and d quarks. The lifetime relation $\tau(\Lambda_c^+)/\tau(D^+) \simeq [1+\tau(D^+)/3\times 10^{-13}s]^{-1}$ is derived, based on the assumption that the spectator model is valid for the D^+.

(ii) For charmed mesons, given $\tau(D^+)/\tau(D^0) = 5-10$, we predict: (a) $\tau(F^+)/\tau(D^+) = 0.7-0.4$, (b) an enhanced $\Delta S = 0$ rate for D^+, (c) a substantial multipion branching fraction for the F^+, (d) an $F^+ \to \tau^+\nu$ branching fraction of order 10-20%, and (e) restrictive bounds on the $D^0 \to \bar{K}^0\pi^0$ mode.

(iii) We give formulae for the B mesons' lifetimes in the one-gluon model, which suggest that nonspectator effects are not as significant for B mesons.

Our analysis is based on the effective weak interaction Lagrangian

$$\mathscr{L}_{eff} = (G_F/\sqrt{2})\ [f_1(\bar{u}d')(\bar{s}'c) + f_2(\bar{s}'d')(\bar{u}c)] \quad ,$$

where $(\bar{q}Q)$ denotes a color singlet V-A current. The short distance enhancement factors f_1 and f_2 due to gluon exchanges are given numerically by

$$f_+ \equiv f_1 + f_2 = 0.69$$
$$f_- \equiv f_1 - f_2 = 2.09 \quad .$$

In the absence of strong interactions $f_+ = f_- = 1$. Here $d' = d\cos\theta + s\sin\theta$ and $s' = s\cos\theta - d\sin\theta$, where θ is the Cabibbo angle, $\sin^2\theta \simeq 0.05$.

II. Λ_c^+ LIFETIME [3]

As a first example of nonspectator contributions, we consider the effect of cd interactins for the Λ_c^+ lifetime. Helicity suppression does not apply here since the initial state contains two quarks. Our approach is to directly calculate the nonspectator contribution to the Λ_c^+ rate in the free quark model, including short-distance enhancement. We use a nonrelativistic approximation for the quarks in the Λ_c^+. The nonspectator contribution is proportional to the square modulus of the wavefunction for two quarks at the origin, $|\psi(0)|^2 \equiv \langle\psi|\delta^3(\vec{r}_1 - \vec{r}_2)|\psi\rangle$ which we estimate from the $\Sigma_c^+ - \Lambda_c^+$ mass difference, using the QCD analogue of the Fermi-Breit hyperfine interaction.

To obtain the inclusive decay rate we integrate over the phase space of the final state quarks, on the assumption that the Λ_c^+ mass is large enough for this to represent (in the usual parton-model fashion) the sum of all hadronic final states. The color antisymmetry of the wavefunction leads to a large enhancement factor $f_-^2 \approx 4$.

We find a nonspectator rate $\Gamma(cd \to su) \simeq 0.32 \times 10^{13} s^{-1}$ to be compared with the estimated spectator rate $\Gamma_{spect.} \simeq 0.2 \times 10^{13} s^{-1}$. To avoid the uncertainties in the latter estimate we use $\Gamma_{spect.} \simeq 1/\tau(D^+)$, i.e., we assume that the conventional dogma (charmed hadron decay = charmed quark decay) is correct for the D^+, where all nonspectator interactions are Cabibbo-suppressed. We thus obtain the lifetime relation

$$\tau(\Lambda_c^+) = \tau(D^+)/[1 + \tau(D^+)/3 \times 10^{-13} s] \quad .$$

With input $\tau(D^+) \simeq 10 \times 10^{-13} s$, we obtain $\tau(\Lambda^+) \sim 2.3 \times 10^{-13} s$ in fair agreement with recent data[1] $\tau(\Lambda_c^+) = 1.14^{+0.90}_{-0.44}$. The poor statistics of the present data preclude serious quantitative comparisons at this point, but the trend of the data is nicely reproduced.

III. CHARMED MESON DECAYS AND LIFETIMES [4]

(a) Lifetimes: The common spectator contributions to the decays of the D^+, D^0 and F^+ are of two types. The nonleptonic contributions $c \to s u \bar{d}$, ... including all radiative corrections will be denoted by N. The semileptonic decays to electrons plus muons, with gluon corrections, will be denoted by L. We shall parametrize these spectator contributions rather than calculate them directly, thereby avoiding the various ambiguities inherent in the quark masses and parton model assumptions.

The contributions of nonspectator diagrams are parametrized as

$$\begin{aligned} \Gamma_g\left(D^0(c\bar{u}) \to s\bar{d};d\bar{d};s\bar{s};d\bar{s}\right) &= (C^4;C^2S^2;C^2S^2;S^4)\ f_1^2 G(D^0) \\ \Gamma_g\left(D^+(c\bar{d}) \to u\bar{d};u\bar{s}\right) &= (C^2S^2;S^4)\ f_2^2 G(D^+) \\ \Gamma_g\left(F^+(c\bar{s}) \to u\bar{d};u\bar{s}\right) &= (C^4;C^2S^2)\ f_2^2 G(F^+) \quad , \end{aligned} \tag{1}$$

where $C = \cos\theta$, $S = \sin\theta$. The strong enhancement factors have been isolated in Eq. (1) for convenience. In the one-gluon model we find

$$G(D^0):G(D^+):G(F^+) = 1:1:r \tag{2}$$

where $r \simeq 0.55$ is an SU(3) breaking factor. An important contribution to the F^+ rate is the $\tau\nu$ decay which is

$$\Gamma_{F\to\tau\nu} = C^2 G_F^2 f_F^2 m_F m_\tau^2 (1 - m_\tau^2/m_F^2)^2/8\pi \quad ,$$

where $f_F^2 = 12|\psi(0)|_F^2/m_F$ in the nonrelativistic approximation. The decay constants f_F, f_D are uncertain at present, but for numerical estimates we use $f_F = f_D \simeq 430$ MeV as suggested by the experimental $D^{*+,0}$ and $D^{+,0}$ mass splittings. Neglecting other purely leptonic decay modes, we obtain the total decay rates:

$$\begin{aligned} \Gamma(D^0) &= L + N + f_1^2 G(D^0) \\ \Gamma(D^+) &= L + N + f_2^2 S^2 G(D^+) \\ \Gamma(F^+) &= L + N + f_2^2 C^2 G(F^+) + \Gamma_{F\to\tau\nu} \quad . \end{aligned} \tag{3}$$

In the one-gluon model, Eq. (2) leads to the lifetime relation:

$$\tau(F^+) = \frac{\tau(D^+)\left(1 - B(F \to \tau\nu)\right)}{[1 + \Delta(rC^2 - S^2)]} \quad ,$$

where

$$\Delta \simeq 0.257[\tau(D^+)/\tau(D^0) - 1] \quad .$$

For $\tau(D^+)/\tau(D^o) \approx 10$ we find $\tau(F^+)/\tau(D^+) \simeq 0.4 - 0.5$, in good agreement with present data.

We note that since one-gluon diagrams do not contribute to decays to leptons, the semileptonic branching fractions into electrons are in the same ratios as the lifetimes in the one-gluon model. However, if multiple gluon emission is important, then the semileptonic branching fraction of the F^+ could be enhanced by the annihilation interaction $c\bar{s} \to e^+\nu_e$ + gluons.

(b) Inclusive $\Delta S = 0$ decays: We now turn to inclusive Cabibbo suppressed $\Delta S = 0$ decays; i.e., transitions in which the final state has the same strangeness as the initial state. In the spectator model the branching fractions for these decays are the same for the D^o, D^+ and F^+, with $B(\Delta S = 0) \approx 8\%$. Including exchange interactions, we find that $\Delta S = 0$ branching ratios are slightly increased to 8-10% for the D^o, whereas for the F^+, $B(\Delta S = 0)$ is constrained to lie in the range 4-8%.

For the D^+, nonspectator interactions contribute only to Cabibbo suppressed decays, and can lead to a significant enhancement of the $\Delta S = 0$ branching fraction. In the one-gluon model with $B_e(D^+) = 0.22$ and $\tau(D^+)/\tau(D^o) = 5$ and 10, we find $B(D^+, \Delta S = 0) = 12\%$ and 17% respectively. There is some indication from the measured $B(D^+ \to \bar{K}X)$ that the $\Delta S = 0$ branching fraction for the D^+ is enhanced.

(c) F^+ multipion decay modes: In F^+ decays the spectator transition $c\bar{s} \to s\bar{s}u\bar{d}$ will give final states with either overt or hidden strangeness (e.g., $F^+ \to K^-K^+X^+$ or $F^+ \to \eta X^+$). Nonresonant multipion final states are not expected at a significant level. The situation is markedly different with the nonspectator transition $c\bar{s} \to u\bar{d}$+gluon(s), where states of three or more pions are anticipated. The branching fraction for this transition with no s or $\bar{s}$ quarks originating from the weak interaction can be estimated in the one-gluon model. We obtain $B(F^+ \to \text{no } s \text{ or } \bar{s}) \simeq (25\text{-}30)\%$. Since $\bar{u}u$ or $\bar{d}d$ pair creation is favored over $\bar{s}s$, the $u\bar{d}g$ final state will evolve mainly into multipion or η plus pions modes. Although we are unable to separate the relative proportion, phase space considerations suggest that the multipion states will predominate. In this connection it is interesting to note that several $F^- \to \pi^-\pi^+\pi^-\pi^o$ events have now been observed.

(d) The "color suppression" puzzle: The spectator model predicts $B(D^o \to \bar{K}^o\pi^o)/B(D^o \to K^-\pi^+) = 0.05$, whereas observed rates for these modes are $B^{oo} = 2.0 \pm 0.9\%$, $B^{-+} = 2.8 \pm 0.6\%$. Nonspectator interactions offer a way out of this discrepancy. This is because gluon-enhanced exchange diagrams give amplitudes in which there is no color suppression factor between the $\bar{K}^o\pi^o$ and $K^-\pi^+$ modes. Hence adding spectator and exchange contributions, we are simply left with an isospin triangle inequality on the $\bar{K}^o\pi^o$ branching fraction

$$\tfrac{1}{2}[(B^{-+})^{\frac{1}{2}} - (B^{o+}\tau^o/\tau^+)^{\frac{1}{2}}]^2 \le B^{oo} \le \tfrac{1}{2}[(B^{-+})^{\frac{1}{2}} + (B^{o+}\tau^o/\tau^+)^{\frac{1}{2}}]^2 \qquad (4)$$

where τ^o, τ^+ denote the D^o, D^+ lifetimes. Using the experimental values $B^{-+} = 2.8 \pm 0.6\%$ and $B^{o+} = 2.1 \pm 0.4\%$, and taking $\tau^+/\tau^o = 5$, we find the numerical bounds

$$0.5 \pm 0.2\% \le B^{oo} \le 2.7 \pm 0.5\% \quad .$$

These bracket nicely the experimental value $B^{oo} = 2.0 \pm 0.9\%$.

The bounds become more restirictive with increasing τ^+/τ^0.

(e) Distinctive decay modes: Special decay modes in which the so-called spectator quark is absent in the final state are of special interest since they can occur only through the nonspectator interaction. An example is the transition $c\bar{u} \to s\bar{d}g$ with an $s\bar{s}$ pair created by the gluon. This would give rise to $D^0 \to \bar{K}^0 K^0 \bar{K}^0$ or $D^0 \to \bar{K}^0 \phi$ decays. A more exotic example is $F^+ \to p\bar{n}$; although certain to be rare, such a decay has a spectacular signature!

IV. B MESON LIFETIMES AND DECAYS

We give a brief summary of the situation for bottom mesons $B_u(b\bar{u})$, $B_d(b\bar{d})$, $B_s(b\bar{s})$ and $B_c(b\bar{c})$. The net spectator contribution with strong enhancement factors included (note for B mesons $f_+ \simeq 0.80$, $f_- \simeq 1.56$) is

$$\Gamma_{\mathrm{spect.}}(B) = \gamma_b[7.69|U_{bu}|^2 + 3.07|U_{bc}|^2] \quad , \tag{5}$$

where

$$\gamma_b^{-1} \equiv (G_F^2 m_b^5/192\pi^3)^{-1} \simeq 0.16 \times 10^{-13}\mathrm{s}$$

and $U_{bu}(U_{bc})$ are the $b \to u$ $(b \to c)$ transition elements. Adding all possible contributions (spectator and nonspectator), we find the decay rates:

$$\begin{aligned} \Gamma(B_d) &= \gamma_b[10.41|U_{bu}|^2 + 4.95|U_{bc}|^2] \\ \Gamma(B_s) &= \gamma_b[\ 8.67|U_{bu}|^2 + 3.75|U_{bc}|^2] \\ \Gamma(B_u) &= \gamma_b[\ 9.67|U_{bu}|^2 + 3.07|U_{bc}|^2] \\ \Gamma(B_c) &= \gamma_b[\ 7.69|U_{bu}|^2 + 5.17|U_{bc}|^2] \end{aligned} \tag{6}$$

These rates are not dramatically different from the spectator rate. The role of non-spectator diagrams in these rates is as follows:

(a) Charged mesons: Annihilation diagrams into final states containing a charmed quark or a τ lepton are neither helicity- nor color-suppressed. However, gluon radiation diagrams are color-suppressed by a factor $(f_+ - f_-)^2/4 \simeq 0.14$.

(b) Neutral mesons: Exchange diagrams to final states with heavy quarks or leptons are not helicity-suppressed but are strongly color-suppressed by a factor $(2f_+ - f_-)^2 \simeq 0.002$. Gluon radiation diagrams are enhanced by $(f_+ + f_-)^2/4 \simeq 1.4$.

For the expected ranges[5] of U_{bc} and U_{bu} we find $10^{-14}\mathrm{s} < \tau(B) < 5.0 \times 10^{-13}\mathrm{s}$.

The semileptonic branching fractions for B_d and B_u mesons are

$$\begin{aligned} B_{e+\mu}(B_d) &= \gamma_b[2.11|U_{bu}|^2 + 0.92|U_{bc}|^2]/\Gamma(B_d) \\ B_{e+\mu}(B_u) &= \gamma_b[2.25|U_{bu}|^2 + 0.92|U_{bc}|^2]/\Gamma(B_u) \quad . \end{aligned}$$

For (i) $U_{bu} = 0$, (ii) $|U_{bu}| = |U_{bc}|$, the predicted semileptonic rates are (i) 19%, (ii) 20% for B_d and (i) 30%, (ii) 25% for B_u.

The expected mean multiplicities of kaons per B-meson arising from strange and charm quarks created in the weak interaction are

$$\langle n_K(B_d)\rangle = \gamma_b[1.9|U_{bu}|^2 + 5.7|U_{bc}|^2]/\Gamma(B_d)$$
$$\langle n_K(B_u)\rangle = \gamma_b[4.3|U_{bu}|^2 + 3.8|U_{bc}|^2]/\Gamma(B_u)$$

which yield (i) 1.1, (ii) 0.5 for B_d and (i) 1.2, (ii) 0.6 for $\underline{B}_u$. We expect these multiplicities to be augmented by 15-20% from $s\bar{s}$ pair creation from the vacuum .

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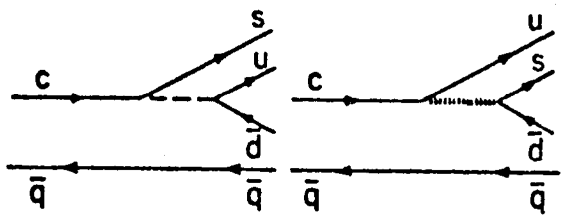
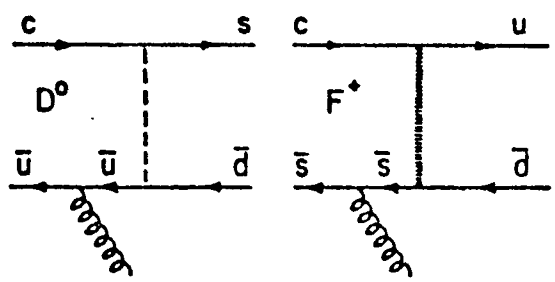
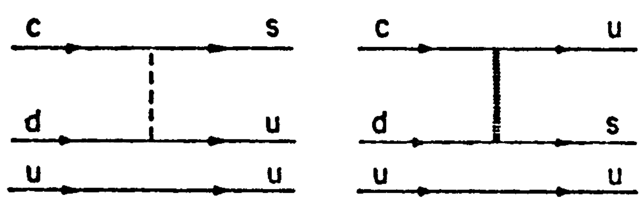


Spectator diagrams
(D^0, D^+, F^+, Λ_c^+ decays)

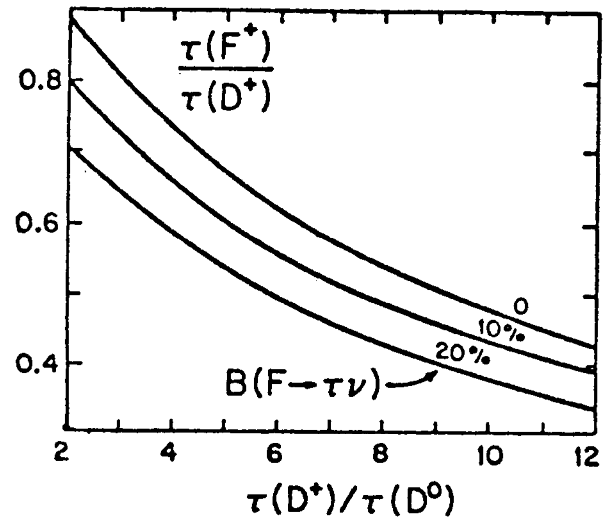


Single gluon emission diagrams

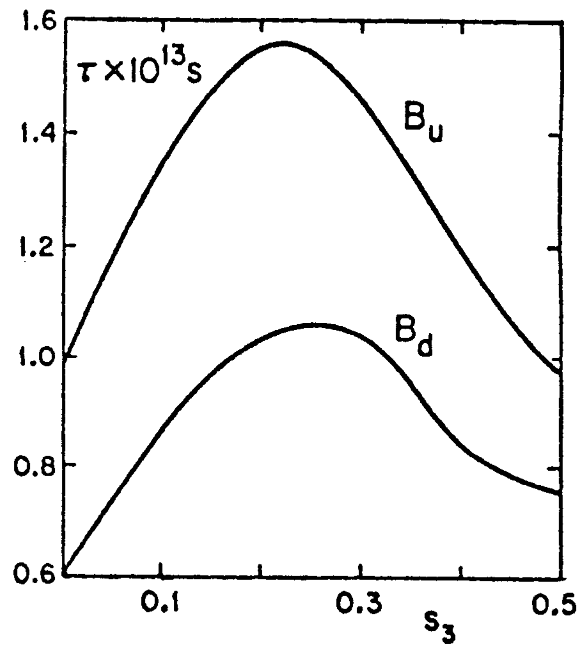


Non-spectator Diagrams
(Λ_c^+ decay)

Note: --- and ▬ correspond to the coefficients of f_1 and f_2 respectively in the effective Lagrangian.



F^+ Lifetime predictions



B- Lifetime predictions vs. the KM parameter s_3, based on Eq.(6) and the analysis of ref. 5 with $B = 0.4$ and $\delta < \pi/2$.