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Remarks on the Differing Lifetimes of Charmed Mesons

S. P. Rosen[(a)]

Theoretical Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

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Differences in the D^+ and D^0 lifetimes may arise either from $\underline{6}$ dominance in the effective nonleptonic Hamiltonian, or from the dominance of a particular W^+-exchange diagram which behaves like a D^0-$\bar{K}^{0*}$ pole. If $\underline{6}$ dominance holds, then the F^+ will have a relatively short lifetime and a small semileptonic branching ratio, just like the D^0; but if W^+ exchange is dominant, the F^+ will have a long lifetime and large semileptonic branching ratio, like the D^+.

Two different experiments[1,2] report evidence that the charged D meson is much longer lived than its neutral companion. In one experiment,[1] the semileptonic branching ratio for D^+ is found to be at least four times the corresponding ratio for D^0; and in the other experiment,[2] direct measurements of the flight paths of charmed mesons in emulsions indicate that the D^+ lifetime is roughly five times the D^0 lifetime. This result is not consistent with the notion that charmed-meson decay is a process in which the charmed quark is the active partner, and the light quark merely a spectator. Here we examine ways in which this notion might be modified to accomodate the differing lifetimes, and discuss tests based on the F^+ lifetime.

In the standard model of quarks and their weak interactions,[3,4] the inclusive semileptonic decays of charmed mesons are all manifestations of the quark transition

$$c \to s + l^+ + \nu_l \tag{1}$$

and, apart from small corrections due to phase space and Cabibbo-suppressed processes, their rates are equal to one another:

$$\Gamma(D^+ \to l^+\nu_l x^0) \approx \Gamma(D^0 \to l^+\nu_l x^-) \approx \Gamma(F^+ \to l^+\nu_l x^0)\,. \tag{2}$$

Differences in lifetimes must therefore arise from the nonleptonic decay modes that are engendered by the coupling of the standard hadronic current to the charged vector boson W^+:

$$H_{NL} = g[(\bar{s}c) + (\bar{d}u) + \dots]W^+ + \text{H.c.} \tag{3}$$

It is well known[3,5] that this interaction leads to an effective Hamiltonian involving the $\underline{6}$ and $\underline{15}^*$ representations of SU(3), and that short-distance effects of quantum chromodynamics (QCD) enhance the $\underline{6}$ component over the $\underline{15}^*$ by a factor of order 3–4. Could this enhancement be responsible for the relatively long lifetime of D^+?

To analyze this question, I note that $\underline{6}$ dominance requires the rate for the exclusive decay $D^+ \to K^-\pi^+$ to be much smaller than the rates for $D^0 \to K^-\pi^+$ and $D^0 \to \bar{K}^0\pi^0$.[5] Experimentally, all three decay modes turn out to have branching ratios in the neighborhood of 2%,[6] and so the absolute rate for the D^+ decay mode will be much smaller than the D^0 decay rates only if the lifetime of D^+ is much longer than the lifetime of D^0.[7] Thus the answer to my question appears, at first sight, to be positive. There are, however, some indications to the contrary from F^+ decay.

Because of the $u \leftrightarrow s$ symmetry properties of the $\underline{6}$ component of the effective Hamiltonian,[8] $\underline{6}$ dominance implies that the F^+ must have approximately the same total nonleptonic decay rate as the D^0. Therefore if the D^0 has a short lifetime and a small (< 4%) semileptonic branching ratio,[1] then so must the F^+. The emulsion experiments in which the D-meson lifetimes were measured[2] also found evidence for the F^+, and so we can test this prediction for its lifetime.

So far, the emulsion experiments[2] have found five candidates for D^0 decay and obtain an average D^0 lifetime of 0.66×10^{-13} sec. In addition, there are four candidates for charged-meson decay: Three of them are ambiguous between F^+ and D^+ and have an average lifetime of 9×10^{-13} sec, while the fourth candidate is unambiguously an F^+ with a lifetime of 3.6×10^{-13} sec. It is too soon to draw a firm conclusion, but it would appear that the lifetime of the F^+ is closer to the D^+ lifetime than to the D^0 one. Should this trend be confirmed in subsequent data, then an alternative to $\underline{6}$ dominance will be needed to explain the differences in charmed-meson lifetimes.

One such alternative can be found by studying quark-model diagrams for charmed-meson decay. In general there are three classes of diagrams. The first class can be thought of as W-radiation diagrams because the charmed quark decays into a strange quark and a W^+ boson, and the W^+ then materializes as a charged lepton-neutrino pair, or as a light quark-antiquark pair [see Fig. 1(a)]. The second class consists of W^+-exchange diagrams in which the charmed quark exchanges a W^+ with the light antiquark inside the meson [see Fig. 1(b)]; and the third class consists of annihilation diagrams in which the meson annihilates into a W^+ which then materializes as a lepton pair or a light-quark pair [see Fig. 1(c)].

At the level of Cabibbo-allowed processes, D^+ decay comes only from W-radiation diagrams, while D^0 decay comes from both W-radiation and W-exchange diagrams. Therefore one reason for the longer D^+ lifetime might be that the W-exchange diagram gives a much larger contribution to the decay rate than the W-radiation ones.

This possibility is at variance with the usual QCD analyses of charm decay which neglect W-exchange because it requires the creation of an additional quark-antiquark pair out of the gluon field.[9] However, it could well be that the D meson is not at a high enough mass for asymptotic-freedom arguments to be the dominant element in its decay. In addition, the W-exchange diagram involves a transition to one or more excited K-meson states, $D^0\to\bar{K}^*$, and as such it resembles the old pole models for strangeness-changing meson and hyperon decays.[10] In these models, the weak interaction acts at the pole, and strong interactions are then responsible for the development of the final hadronic state.[11] With these observations in mind, I explore the consequences of W-exchange dominance for F^+ decay.

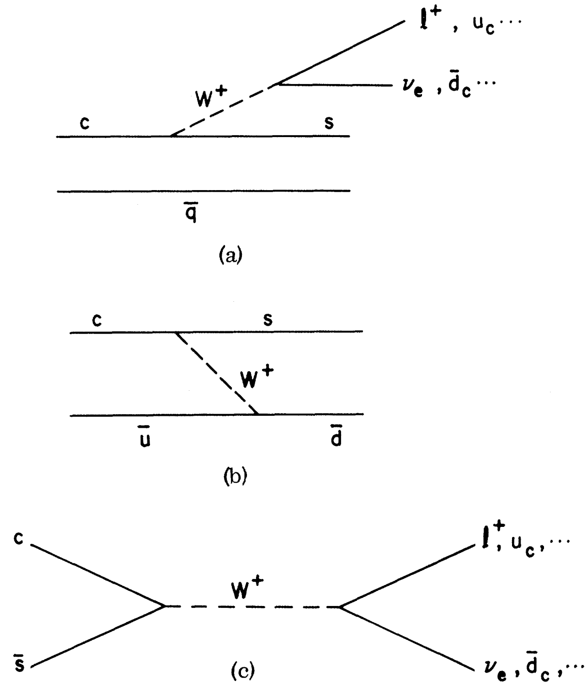

FIG. 1. Quark diagrams for charmed-meson decay: (a) W-radiation diagrams; (b) W-exchange diagram; (c) annihilation diagram.

The decay of the F^+ meson is engendered by W-radiation and annihilation diagrams [Figs. 1(a) and 1(c)], but not by W exchange. Moreover, it can be argued that the annihilation diagrams make only a small contribution to the total rate. Following Fakirov and Stech,[9] I can show that the combined branching ratio for $\mu^+\nu$ and $\tau^+\nu$ final states is

$$B(F^+\to l^+\nu)\approx[0.36\times n\times(f_F/f_K)^2]\%, \qquad (4)$$

where f_F and f_K are the usual decay constants of the F^+ and K^+ mesons, respectively, and n appears in the F^+ lifetime:

$$\tau(F^+)\approx n\times10^{-13}\ \text{sec}. \qquad (5)$$

Various estimates in the literature[12] suggest that

$$(f_F/f_K)^2\lesssim2 \qquad (6)$$

and so, even if n were as large as 10, the branching ratio for purely leptonic decays would be less than 8%. If, as seems reasonable,[13] the contribution of the annihilation diagram to nonleptonic decay modes is roughly equal to, or less than, the purely leptonic decay rate, then the annihilation diagram will contribute less than 15% to the F^+ decay rate. Thus the decay of the F^+ is dominated by W-radiation diagrams.

Now the observed semileptonic branching ratio for D^+ decay, namely[1]

$$B(D^+ \to e^+\nu_e X) = (23 \pm 6)\%, \tag{7}$$

is quite close to the canonical value[5] of 20%, and it suggests that W-radiation diagrams do behave very much like the decay of quasifree quarks[5] [see for example Eq. (1)]. This being so, I would expect the F^+ to have much the same general properties as the D^+: Its lifetime should be equal to that of D^+ (give or take 20%) and be much longer than that of D^0; and its inclusive semileptonic branching ratio should be in the neighborhood of 20%. The first indications of the data are consistent with the lifetime prediction,[2] and so it will be most interesting to measure the semileptonic branching ratio.

To summarize the preceding remarks, I have put forward two possible explanations for the apparent difference in lifetimes between the D^0 and D^+ mesons, and I have found that the properties of the F^+ can distinguish between them. If $\underline{6}$ dominance is the correct explanation, then the lifetime and inclusive semileptonic branching ratio of the F^+ will be approximately the same as the corresponding properties of D^0; and if W-exchange dominance is correct, then the F^+ will have general properties similar to those of the D^+. Preliminary experimental data favor the latter explanation, but are not yet conclusive.

In conclusion, it is amusing to extend the notion of W-exchange dominance (or equivalently the pole model) into the realms of B-meson and charmed-baryon decay. If the dominant weak decay of the b quark is $b \to c + W^-$, then pole diagrams of the form $B^0 \to D^{0*}$ can occur in neutral-B-meson decay, but not in charged-B-meson decay. Therefore, if the effects of asymptotic freedom have not succeeded in suppressing W-exchange diagrams by the time we reach the b-quark mass (~ 5 GeV), then the neutral B mesons could well have shorter lifetimes and smaller semileptonic branching ratios than their charged counterparts.

For charmed baryons, W exchange can lead to transitions $(cd) \to (su)$ within the three-quark system (see Fig. 2). In contrast to the case of mesons, the two-quark initial and final states behave as color $\underline{3}^*$'s rather than singlets. Thus while W exchange may dominate meson decay, it need not

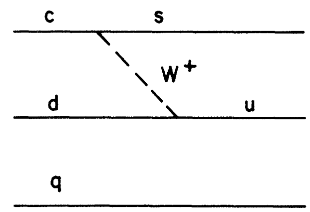

FIG. 2. W exchange in charmed-baryon decay.

dominate baryon decay. However, if it does, then then states like (cdd) will have much shorter lifetimes than states containing no d quarks, for example, (cuu) and (cus).

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Note added.—After this work was completed, the author received a preprint by M. Bander, D. Silverman, and A. Soni [Phys. Rev. Lett. $\underline{44}$, 7 (1980) (this issue)], in which a dynamical argument is given for the enhancement of a diagram involving W exchange and gluon radiation. We also received a preprint from C. Quigg [Fermilab Report No. Pub-79/62-THY (unpublished)] which emphasizes the implications of sextet dominance for the lifetimes of D^0 and F^+.

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Mechanism for the Difference in Lifetimes of Charged and Neutral D Mesons

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, Irvine, California 92717

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The reaction $D^0 \to s + \bar{d} +$ gluon is proposed as a source for the difference in the lifetimes of the charged and neutral D mesons. In a nonrelativistic bound-state model the rate for the reaction is found to depend on the ratio f_D/m_u. For reasonable values of this ratio the observed difference in the lifetimes may be accounted for.

A number of experiments[1] have recently reported a significant difference in the lifetimes of the charged and neutral D mesons, with $\tau_{D^\pm}$ perhaps as much as six times as large as τ_{D^0}. It has been argued that mesons containing a heavy quark c, b, or t will decay through a mechanism where the light quark acts as a spectator[2] [Fig. 1(a)]. The process depicted in Fig. 1(b) can contribute only to the decay of the D^0.[3] However, by the usual helicity arguments the contribution of Fig. 1(b) is suppressed by the square of the ratio of light-to heavy-quark masses and by f_D^2/m_c^2, f_D being the pure leptonic decay constant of the D defined by

$$\langle D(p)\,|\,J_\mu{}^A|\,0\rangle = \frac{-i}{(2\pi)^{3/2}}\,\frac{f_D p_\mu}{(2\omega_D)^{1/2}}\,, \qquad (1)$$

where J^A is the weak hadronic axial-vector current. The spectator graph leads to equal charged and neutral decay rates given by[4]

$$\Gamma_{\rm sp} = \Gamma_\mu (m_c/m_\mu)^5 [2 + 3a_3], \qquad (2)$$

where $\Gamma_\mu = G_F{}^2 m_\mu{}^5/192\pi^3$ is the rate for muon decay $\mu \to e\nu_\mu\nu_e$. The factor of 2 is for leptons, and 3 for colors, and $a_3 = (2f_+{}^2 + f_-{}^2)/3$. The coefficients f_+ and f_- incorporate renormalization effects due to gluon exchange on the terms in the weak Lagrangian transforming as the $\underline{20}$ and $\underline{84}$ of SU(4), respectively.[5] Using $\alpha_s(m_c{}^2) = 0.6$, we obtain $f_- \sim 2$ and $f_+ \sim 0.7$, leading to $a_3 = 1.7$.

In this note, we propose a mechanism that may account for the observed difference in lifetimes. It is the one depicted in Fig. 2, namely,

$$D^0 \to s + \bar{d} + \gamma_s(\text{gluon})\,. \qquad (3)$$

We have calculated the contribution of this process by considering the D^0 meson (mass = 1.86 GeV) as a nonrelativistic bound state of c and u quarks with "constituent" quark masses of $m_c \sim 1.55$ GeV and $m_u \sim 0.3$ GeV. The momentum variation of the bound-state wave function is faster than that

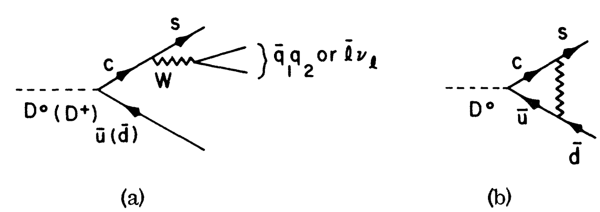

FIG. 1. Graphs contributing to D-meson decays. (a) The "spectator" graph that contributes to the nonleptonic and semileptonic decays of both the charged and the neutral D mesons. (b) This contributes to the decays of the D^0 ($\bar{D}^0$) only. See Ref. 3.