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by

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COMMENTS ON THE DIFFERING LIFETIMES OF CHARMED HADRONS

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Theoretical explanations of the observed lifetime differences of weakly decaying charmed hadrons are briefly reviewed. It is argued that the previous uncertainties in determining the dominant dynamical origin of the D^+-D^0 lifetime difference are resolved by the recent development of a consistent theory of two-body decays which constitute a large fraction of all nonleptonic D decays. Predictions on the lifetime hierarchy of charmed baryons are also presented.

Much experimental and theoretical work has been devoted to the lifetime differences of weakly decaying charmed hadrons since the discovery of this originally unexpected fact in 1979. The present experimental status is summarized in Table 1. We see that

$$\tau(D^+) > \tau(D^0) \simeq \tau(D_c^+) \qquad (1)$$
$$\tau(\Lambda_c^+) < \tau(D^0),\ \tau(\Lambda_c^+) < \tau(\Xi_c^+)$$

where the inequalities amount to factors 1.5-2.5. In the meantime, also theory has recognized that lifetime differences ought to be expected at some level due to non-asymptotic bound state effects. However, the usual calculational problems with QCD in the nonperturbative confinement regime and uncertainties in the choice of some parameters such as the scale in $\alpha_s(\mu^2)$ and effective quark masses have made it difficult to pin down the dominant origin of the lifetime differences and to arrive at firm quantitative estimates (5). The situation has changed considerably with the recent progress accomplished on the experimental side, in particular by the Mark III collaboration (6), and the simultaneous development of a respectable theory of exclusive decays (7-9). In this talk, I shall describe the more solid understanding of the hierarchy of lifetimes which has emerged from these symbiotic efforts.

	$\tau[10^{-13}\text{sec}]$		$B_{SL}[\%]$	
D^+	$10.31^{+0.52}_{-0.44}$	(1)	$17.0\pm1.9\pm0.7$	(3)
D^0	$4.30^{+0.20}_{-0.19}$	(1)	$7.5\pm1.1\pm0.4$	(3)
D_c^+	$3.5\ ^{+0.6}_{-0.5}$	(1)	-	
Λ_c^+	$1.9\ ^{+0.5}_{-0.3}$	(1)	4.5 ± 1.7	(4)
Ξ_c^+	$4.8\ ^{+2.9}_{-1.8}$	(2)	-	

Table 1: Charmed particle lifetimes and semileptonic branching ratios

The common starting point of theoretical considerations of weak decays is an effective Hamiltonian (10) derived from the charged current interactions of the standard electroweak gauge model and incorporating short-distance QCD corrections. In the case of Cabibbo-allowed nonleptonic charm decays, one has (5)

$$H_{NL}^{eff} = (G_F/\sqrt{2})(c_+O_+ + c_-O_-) \qquad (2)$$
$$O_\pm = (\bar{u}d)_L(\bar{s}c)_L \pm (\bar{s}d)_L(\bar{u}c)_L$$

where $(\bar{a}b)_L = \bar{a}\gamma\mu(1-\gamma_5)b$ and $c_- = c_+^{-2} = [\alpha_s(m_c^2)/\alpha_s(m_W^2)]^{0.48}$. The decay amplitudes are then given by matrix elements of H_{NL}^{eff} between hadronic states. It is mainly our present inability to calculate $\langle O_\pm\rangle$ from first principles which gives rise to ambiguities and quantitative uncertainties. Making use of hadron-quark duality which is known to work in other applications such as $e^+e^-\to$hadrons and spectroscopy (11) one can approach lifetime questions in heavy flavor decays in two ways: "exclusively" by considering the (dominant) physical decay channels,

$$\tau^{-1} = \Sigma[\Gamma(l\nu_l\text{hadrons}) + \Gamma(\text{hadrons})], \qquad (3)$$

and "inclusively" by studying the dual decays into free quarks,

$$\tau^{-1} = \Sigma[\Gamma(l\nu_l\text{quarks}) + \Gamma(\text{quarks})]. \qquad (4)$$

The "exclusive" way is in principle more straightforward, but more difficult in practice. It involves hadronic physics in its full complexity. The "inclusive" way, on the other hand, is conceptually simpler, but less direct and a priori approximative.

Table 2 exemplifies expectations on the D meson lifetimes and semileptonic branching ratios resulting from the inclusive approach. The numbers represent typical estimates and are subject to considerable uncertainties as

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	approximations	$B_{SL}(D^0)$	$B_{SL}(D^+)$	$\frac{\tau(D^+)}{\tau(D^0)}$
(a)	spectator model free quarks	20%	20%	1
(b)	spectator model QCD corrected	15%	15%	1
(c)	including quark interference	15%	19%	1.3
(d)	dropping non-leading terms in $1/N_C$	12%	19%	1.6
(e)	including W-exchange	<12%	19%	>1.6

Table 2: Theoretical expectations from the inclusive description of D decays

discussed extensively in the literature (5). A few comments are in order:

(a) The quark predictions simply reflect the number of available decay channels.

(b) Short-distance QCD corrections enhance the nonleptonic decay rates and, hence, decrease the semileptonic branching ratios, but of course do not affect the equality of the lifetimes in the spectator model (12).

(c) Quark interference is a consequence of the Pauli principle (13) and occurs in the decay $D^+=[\bar{d}c]\to\bar{d}su\bar{d}$ due to the presence of two identical quarks ($\bar{d}$) in the final state. No such interference takes place in Cabibbo-allowed D^0 decay. As a result, the lifetime of the D^+ is lengthened in comparison with the D^0 and the semileptonic branching ratio $B_{SL}(D^+)$ increases (13,14).

(d) The prescription to expand the nonleptonic rates in powers of $1/N_C$, N_C being the number of color degrees of freedom, and to drop all non-leading terms is suggested by two arguments. Firstly, in the previous approximations one has added up both leading and certain non-leading contributions, from the point of view of the $1/N_C$-expansion, but has neglected many other non-leading terms. Since the latter are difficult to calculate due to the genuine nonperturbative nature of the $1/N_C$-expansion it appears more consistent (8,15) to drop all non-leading terms. Secondly, a similar procedure (8) remarkably improves the agreement between theory and experiment in the case of two-body decays as discussed later. The net effect of following the above prescription is a stronger nonleptonic enhancement of the spectator model rates accompanied by a similar reinforcement of the destructive interference in the D^+ case. Thus, the lifetime and semileptonic branching ratio of the D^0 decrease in comparison with (b) and (c), whereas the expectation (c) on the D^+ is little affected (8).

(e) W-exchange between the charm quark and the light constituent quark is only possible in D^0 decay, $D^0=[\bar{u}c]\to\bar{d}s$, but not in Cabibbo-allowed D^+ decay. Thus, W-exchange potentially shortens the lifetime of the D^0 relative to the D^+ and decreases $B_{SL}(D^0)$ as desired. However, the effect is totally negligible unless, due to the presence of gluons in the D^0 (16), the $\bar{u}c$-component has a large probability to carry spin 1. It is clearly very difficult (5) to obtain a reliable estimate of this probability.

To conclude, the inclusive approach provides a qualitative understanding of the observed D^+-D^0 lifetime difference as arising from destructive quark interference (D^+) and/or gluon enhanced W-exchange (D^0). However, interference does not appear efficient enough to explain the whole effect quantitatively while the gluon enhancement of W-exchange is extremely difficult to quantify at all. Hence, the dominant dynamical origin of the D^+-D^0 lifetime difference remains somewhat dubious.

Recently, in response to the large amount of Mark III data (17), theory has focussed on exclusive decays. These data indicate that the two-body channels (including resonances) constitute a large fraction of all nonleptonic D decays. Given this fact it is clear that the correct theory of two-body decays will also explain the major part of the D^+-D^0 lifetime difference. Despite the notorious problems (5) one encounters in developing a reliable quantitative framework one has finally succeeded as I believe. I shall briefly describe the main recent steps towards a consistent theory and point out the implications on the lifetime issues raised above.

Bauer, Stech and Wirbel (7) have performed a comprehensive phenomenological analysis of two-body decays assuming
(A) factorization of $\langle H^{eff}_{NL}\rangle$ in products of matrix elements of quark currents. Approximating the various form factors by the nearest meson pole and taking into account known final state interactions they have shown that consistency with the Mark III data requires the additional assumption
(B) of no color mismatch, i.e. formation of final mesons only from quarks which belong to the same color singlet currents in eq.(2). As a direct consequence of assumption (A), contributions from W-exchange (and annihilation) vanish in the chiral limit and, hence, are negligible. Adding up the exclusive rates for $D\to PP$, PV, VV, $l\nu_l P$, $l\nu_l V$ where P and V denote pseudoscalar and vector mesons, respectively, one obtains the partial lifetimes

$$\tau \approx \begin{cases} 5.6\cdot10^{-13} \text{ sec for } D^0 \\ 11.3\cdot10^{-13} \text{ sec for } D^+. \end{cases} \qquad (5)$$

Eq.(5) and Table 1 imply that the above channels account for 80-90% of the total D^0 and D^+ decay widths. More importantly, the lifetime ratio $\tau(D^+)/\tau(D^0) \approx 2$ following from eq.(5) originates solely in destructive interferences of D^+ amplitudes. It thus becomes clear that interference is also the dominant origin of the inclusive D^+-D^0 lifetime difference, provided somebody proves the crucial assumptions (A) and (B) stated above. A second problem to be solved in this model is the $\bar{K}^0\phi$ puzzle. The decay $D^0 \to \bar{K}^0\phi$ has been observed in several experiments (18) with a branching ratio ~ 1%, a value at least one order of magnitude larger than expected (19) unless this channel is strongly fed by final state interactions (20).

Buras, Gérard and the speaker (8) have systematically applied $1/N_C$-expansion techniques developed for strong interaction meson physics (21) to weak decays of mesons. They have shown that to leading order in $1/N_C$ the mesonic matrix elements of four-quark operators factorize and that there is no color mismatch. The next-to-leading order in $1/N_C$ then includes factorizable as well as non-factorizable contributions and also the final state interactions. In the original estimates (22) the non-leading factorizable terms have been added to the leading ones, whereas all other non-leading contributions have been neglected. This is theoretically inconsistent and has caused serious phenomenological problems (5) in channels like $D^0 \to \bar{K}^0\pi^0$. On the other hand, if only the leading terms in the $1/N_C$-expansion are kept the assumptions (A) and (B) quoted before hold exactly and one arrives essentially at the phenomenologically successful model of Bauer et al. (7). Thus, if one can further prove that the non-leading contributions are indeed small despite the worrying fact that $N_C=3$ is not a very big number, the main problem is solved. Of course, the $\bar{K}^0\phi$ puzzle still needs to be explained.

Both of the remaining tasks have been accomplished by Blok and Shifman in a recent series of papers (9). Using QCD sum rule methods they have actually calculated the non-factorizable amplitudes. I repeat, these are the previously unknown next-to-leading terms in the $1/N_C$-expansion (8). The important results for the present discussion can be summarized as follows:

1) In most channels the non-leading factorizable and non-factorizable contributions to the c-quark decay amplitudes cancel to a large extent. This justifies the truncation of the $1/N_C$-expansion anticipated in ref.(8).

2) No such cancellation occurs in the W-exchange (or annihilation) amplitudes since the factorizable terms vanish in the chiral limit as pointed out earlier. The non-factorizable terms, on the other hand, contribute only ~ 20% to the inclusive width of the D^0. This is nicely consistent with their non-leading (in $1/N_C$) nature. Nevertheless, the contribution to the special $D^0 \to \bar{K}^0\phi$ channel is sufficient to explain the observed (18) branching ratio ~ 1%.

In summary, a consistent theory of two-body decays has emerged which is in satisfactory quantitative agreement (7-9) with the existing data (17). Final state interactions, not considered in refs.(8,9) and only partially in ref.(7), need some further thoughts. However, the latter deficiency does not call in question the following conclusion.

The physics of two-body decays provides substantial evidence for destructive interferences of D^+ decay amplitudes as the main origin of the observed D^+-D^0 lifetime difference. The existence of these interferences can be traced to the presence of two identical quark flavors in the decay $D^+ = [\bar{d}c] \to \bar{d}su\bar{d}$. One thus returns to the same picture suspected in the inclusive valence quark description. This picture can be further tested in F^+ and charmed baryon decays.

I finish my talk with a few remarks on charmed baryon lifetimes. Similarly as in meson decays, interference effects are expected (5,23-25) to give rise to lifetime differences. However, in contrast to the meson case, W-exchange between valence quarks of baryons is not helicity suppressed. Hence, it should have more pronounced influence on the lifetime pattern (23-26). Typical quark model estimates (24) yield

$$\Gamma_{dec} : \Gamma^-_{int} : \Gamma^+_{int} : \Gamma_{W\text{-}exch} \approx \qquad (6)$$

$$\approx \begin{cases} 1 : -0.6 : +0.9 : 2 & \text{nonrel.} \\ 1 : -0.2 : +0.4 : 0.6 & \text{bag.} \end{cases}$$

The appearence of two interference terms with opposite signs corresponds to the presence of two light valence quarks in charmed baryons. Depending on the quark structure of Λ_c^+, $\Xi_c^{+,0}$ and Ω_c^0, the non-spectator effects contribute in different combinations to the inclusive non leptonic widths and thus generate a rather unique lifetime hierarchy. From eq.(6) one predicts (24)

$$\tau(\Omega_c^0) : \tau(\Xi_c^0) : \tau(\Lambda_c^+) : \tau(\Xi_c^+) \approx \qquad (7)$$

$$\approx \begin{cases} 0.6 : 0.6 : 1 : 1.6 & \text{nonrel.} \\ 0.7 : 0.7 : 1 : 1.2 & \text{bag.} \end{cases}$$

Qualitatively, the resulting pattern is completely determined by the general properties of H^{eff}_{NL} and the baryonic bound states and can be predicted reliably. On the other hand, the actual size of the lifetime differences is subject to the usual uncertainties of the inclusive approach as exemplified in eqs.(6) and (7). It is , therefore, reassuring to see similar lifetime ratios emerging from an analysis of two-body decays (27):

$$\hat{\tau}(\Omega_c^0) : \hat{\tau}(\Xi_c^0) : \hat{\tau}(\Lambda_c^+) : \hat{\tau}(\Xi_c^+) \approx \tag{8}$$

$$\approx 0.7 : 0.7 : 1 : 2.$$

At any rate, it appears relatively easy to disentangle and determine the individual effects from interference and W-exchange (24), once sufficiently accurate data become available. The observed lifetime differences of D^0, Λ_c^+ and Ξ_c^+ exhibited in Table 1 and eq.(1) follow the expectation that the Λ_c^+ decays fastest because of W-exchange. This lends further support to the overall picture presented in this talk.

I want to thank my collaborators, in particular A.J. Buras, J.-M. Gérard and B. Guberina, for sharing their experience in this field with me. I also apologize for neither having expressed other points of view nor given a more complete list of references. This is only due to the lack of space.

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