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THE ANNIHILATION DIAGRAM IN THREE-BODY D-MESON DECAY[☆]

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We discuss some features of three-body decays of the D meson which are puzzling from the standpoint of the annihilation diagram. As a result, we (1) provide an upper bound on the lifetime ratio of D's, $\tau_D^0/\tau_D^+ < 2.5 \pm 3.4$ and (2) argue that the puzzles are resolved, even if somewhat inelegantly, if final state interactions generate the annihilation diagram.

Charmed particle decays have proven considerably more difficult to understand than originally anticipated. Early optimism led to incorrect predictions of equal D^0 , D^+ lifetimes and of suppression of $D^0 \rightarrow \bar{K}^0 \pi^0$ relative to $D^0 \rightarrow K^- \pi^+$, both based on dominance of the simple "W-radiation" diagram [1]. The resolution of these problems has been to assume dominance of the so-called "annihilation diagram" of fig. 1a [2-5]. Because the annihilation diagram can only affect D^0 decay, the D^0 rate is enhanced over that of D^+ . This diagram necessarily leads to purely $I = 1/2$ final states, and thus explains the ratio [6]

$$(D^0 \rightarrow K^0 \pi^0)/(D^0 \rightarrow K^- \pi^+) = 0.7^{+0.5}_{-0.3}, \quad (1)$$

which is expected to be one half in a purely $I = 1/2$

final state and at the several per cent level in the W-radiation picture. Other consequences of $I = 1/2$ dominance have been discussed by Rosen [3]. The annihilation contribution was originally ascribed to the perturbative diagram of fig. 1b [2]. However, Suzuki has recently argued that this in itself is insufficient, and non-perturbative physics must enter [4]. On the other hand, it has also been noted that the annihilation diagram is analogous to an s channel $I = 1/2$ resonance in the final state system [5], fig. 1c. In ref. [5], we showed specifically how final state interactions, through an s channel scalar resonance, can produce agreement with the data on two body modes and the lifetime ratio. Whatever its origin, something analogous to the annihilation diagram appears necessary in order to explain the data.

This general picture, however, runs into serious trouble when confronted with new data on the $\rho \bar{K}$ final state. The $\rho \bar{K}$ modes can be parameterized by isospin amplitudes for the final state assuming $\Delta I = 1$ for the weak hamiltonian.

$$A(D^0 \rightarrow K^0 \rho^0) = A_{1/2} - A_{3/2},$$

$$A(D^0 \rightarrow K^- \rho^+) = \sqrt{2} A_{1/2} + A_{3/2}/\sqrt{2}, \quad (2)$$

$$A(D^+ \rightarrow \bar{K}^0 \rho^+) = (3/\sqrt{2}) A_{3/2}.$$

The data [6]

$$\Gamma(D^0 \rightarrow \bar{K}^0 \rho^0)/\Gamma(D^0 \rightarrow K^- \rho^+) = 0.01^{+0.06}_{-0.01}, \quad (3)$$

requires $A_3 = (0.8 \pm 0.3) A_1$, in clear contradiction to the $I = 1/2$ final state rule required by the annihilation

Fig. 1. (a) The generic annihilation diagram; (b) a lowest order perturbative contribution to the annihilation diagram; (c) final state interaction mechanism for the annihilation diagram.

diagrams. It is amusing to note that this ratio is about what one would predict using only the W-radiation diagram with no annihilation terms. When one subtracts out the $K\rho$ contributions to the $K\pi\pi$ final state (as we will do below) the remaining rates in that channel are consistent, due to sizable errors, with either $I = 1/2$ dominance or a large $I = 3/2$ component. Thus, as yet, there is no evidence that $I = 1/2$ final states dominate in $K\pi\pi$, and a clear indication of $I = 3/2$ in $K\rho$.

In this note we discuss the $K\rho$ and $K\pi\pi$ system, with emphasis on this puzzle. Among other things we will argue that the problem can be resolved in a natural but somewhat inelegant way if the annihilation diagrams, to the extent that they exist, are generated by s channel resonances in the final state.

The data relevant for the three body decays is listed in table 1 [6]. We also are interested in the non-resonant portion of $D \rightarrow K\pi\pi$. The resonant contributions — $K\rho$ and $K^*\pi$ — can be subtracted out, assuming that their ratios add incoherently, to yield "direct" branching ratios, which we will denote by a tilde,

$$\tilde{B}(D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-) = 1.7 \pm 1.2,$$

$$\tilde{B}(D^0 \rightarrow K^- \pi^+ \pi^0) = 0.1 \pm 4.0,$$

$$2.1 \pm 0.8 < \tilde{B}(D^+ \rightarrow K^- \pi^+ \pi^+) < 4.6 \pm 0.8. \quad (4)$$

The mode $D^+ \rightarrow \bar{K}^0 \pi^0 \pi^+$ cannot be so treated because the $\bar{K}^0 \rho^+$ mode is not measured. However, this process is useful for another reason in that it allows us to bound $R = \tau(D^+)/\tau(D^0)$ from above. The near can-

cellation of A_1 and A_3 in eqs. (1), (2) requires a sizeable $D^+ \rightarrow \bar{K}^0 \rho^+$ amplitude (roughly equal to $D^0 \rightarrow K^- \rho^+$). Moreover, the effect of this mode is enhanced by the small D^+ total rate, leading to a relatively large prediction for the branching ratio. However, there exists an upper limit to this branching ratio from the observed total $\bar{K}^0 \pi^+ \pi^0$ fraction. This can be worked backwards to provide a bound on R . In general, this procedure would not be used due to the existence of an additional parameter — a possible relative phase between A_1 and A_3 . However, the existence of a large cancellation of A_1 and A_3 , requires that amplitudes must be nearly relatively real, and the phase just adds merely a small uncertainty to the bound. Applying this procedure then yields

$$R < 2.5 \pm 3.4. \quad (5)$$

Combined with experiments which require [6]

$$R > 3.1 \pm \frac{4.6}{1.4}, \quad (6)$$

this provides a strong constraint on the lifetimes. For the allowed values of R , the $\bar{K}^0 \rho^+$ mode dominates the direct $\bar{K}^0 \pi^+ \pi^0$ decay. Indeed, $\tilde{B}(D^+ \rightarrow \bar{K}^0 \pi^+ \pi^0) \approx 0$ within errors.

If we assume that the direct $D \rightarrow K\pi\pi$ data can be parameterized by a totally symmetric final state configuration^{†1} with isospin 1/2 and 3/2 [7], then

$$\tilde{B}(D^0 \rightarrow K^0 \pi^+ \pi^-) = 2|C_{1/2} + \frac{1}{2}C_{3/2}|^2,$$

$$\tilde{B}(D^0 \rightarrow K^- \pi^+ \pi^0) = \frac{9}{4}|C_{3/2}|^2,$$

$$\tilde{B}(D^0 \rightarrow \bar{K}^0 \pi^0 \pi^0) = |C_{1/2} - C_{3/2}|^2,$$

$$\tilde{B}(D^+ \rightarrow K^- \pi^+ \pi^+) = 9|C_{3/2}|^2 R,$$

$$\tilde{B}(D^+ \rightarrow \bar{K}^0 \pi^+ \pi^0) = \frac{9}{4}|C_{3/2}|^2 R. \quad (7)$$

From the data, eq. (4), one can obtain

$$\frac{0.26 \pm 0.20}{R} < \left| \frac{C_{3/2}}{C_{1/2} + \frac{1}{2}C_{3/2}} \right|^2 < \frac{0.59 \pm 0.43}{R}. \quad (8)$$

For $R = 5$, this translates into bounds on the relative

^{†1} There may also be a final state involving two relative P waves. We assume that the $\bar{K}\rho$ and $\bar{K}^*\pi$ modes account for this entirely. At present this is compatible with the data.

Table 1
Data relevant for the three body decays of D^0 and D^+ , from ref. [6].

	Mark II	Lead glass wall	Average
$D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-$	3.8 ± 1.2	4.0 ± 1.3	3.9 ± 0.9
$\rightarrow K^- \pi^0 \pi^+$	8.5 ± 3.2	12.0 ± 6.0	9.3 ± 2.8
$\rightarrow K^- \rho^+$	7.2 ± 2.5		
$\rightarrow \bar{K}^0 \rho^0$	$0.1^{+0.4}_{-0.1}$		
$\rightarrow K^{*-} \pi^+$	3.2 ± 1.0		
$\rightarrow \bar{K}^{*0} \pi^0$	$1.4^{+1.9}_{-1.4}$		
$D^+ \rightarrow K^- \pi^+ \pi^+$	6.3 ± 1.5	3.9 ± 1.0	4.6 ± 0.8
$\rightarrow \bar{K}^0 \pi^+ \pi^+$	12.9 ± 8.4		
$\rightarrow \bar{K}^{*0} \pi^+$	< 3.7		

amplitudes

$$0.23 \pm 0.10 < \left| \frac{C_{3/2}}{C_{1/2}} \right| < 0.49 \pm 0.18. \quad (9)$$

The $I = 1/2$ amplitude is larger, but not by much. It is possible to obtain enhancements of this size solely from the QCD short distance coefficient functions [8]. There *may* be some slight need for a form of annihilation process, although, due to the large errors, the strength required is not clear.

Our previous work discussed the $K\pi$ channels and showed how a $J^P = 0^+$ state near 1.4 GeV could be responsible for the enhancement of the $I = 1/2$ final state in a way consistent with the D^0/D^+ lifetime ratio. A positive parity resonance can only couple to $K\pi$, $K3\pi$ etc. There is a similar resonance with quantum numbers $J^P = 0^-$ near 1.4 GeV, the $K'(1400)$. This could in principle produce similar effects if it mixes with the D^0 through the parity conserving weak interaction.

What is especially interesting about this resonance is that it does not appear to couple to $K\rho$. Brandenburg et al. [9] see this resonance in the S-wave configuration $K\epsilon$, with a weak coupling to $K^*\pi$ but very little, if any, to $K\rho$. The $K\rho$ phase shift remains constant (near 180°) throughout this region. Thus, even if the $K'(1400)$ appears strongly in the $I = 1/2$ final state, one is forced to exempt $K\rho$ from an $I = 1/2$ dominance rule. This is only an empirical reason for not having $K\rho$ participate in these final state interactions. However, it is natural in that no adjusting of parameters is needed.

At present the $K^*\pi$ data is not sufficiently accurate to provide a test of the isospin content of this final state. However, in our model there is no reason to expect much of an $I = 1/2$ dominance. The coupling to the resonance is weak enough that this would not be the sole factor determining the structure of the amplitude. The QCD coefficient functions generally suppress $I = 3/2$ effects somewhat (although this is not evident in the $K\rho$ channel), but we would expect no further suppression.

The D^+/D^0 lifetime ratio requires that some mechanism enhance the $I = 1/2$ final state in many but not all channels. Present data indicates that $I = 1/2$ dominance in $K\pi$, but not in $K\rho$, with "direct" $K\pi\pi$ unclear. A final state interaction mechanism is compatible with this pattern, and predicts that the $I = 1/2$ final state *should* be enhanced in $K3\pi$. Further experimental

studies of other modes, and a general improvement in the errors, would make the situation more clear.

The different models for the generation of the annihilation diagram can be tested by the study of B decays. In our picture there will be no annihilation diagram in the B system because there are no nearby resonances. The B^0 and B^- lifetimes would then be very nearly equal. However, in other frameworks such as the perturbative approach, the annihilation diagram could still occur and one would expect differences in the B^0 and B^- lifetimes. This may prove testable through a study of the B semileptonic branching fractions.

In addition, it is possible that naive calculations may be more reasonable in B and T mesons. The energy released is large and final state interactions may not be important except in regions of phase space where two particles have a small invariant mass. If the data is sufficient (a crucial caveat), quark model ideas may be applicable to at least a sensibly selected subset of the decays.

If this picture is in fact correct, the outlook for theoretical studies of D decay is unfortunately discouraging. The motivation for studying D decays is primarily to learn more about weak nonleptonic processes and perhaps obtain some information about quark dynamics. If indeed the decays of charmed mesons are dominated by "odd fashioned" resonance physics, then it is unlikely that much of the desired knowledge will be forthcoming. This is perhaps not too surprising given that D mesons are located right in the resonance region. However, the physics of B meson, and eventually T meson, decays may be more fruitful. Besides yielding information on the origin of the annihilation diagram, they may prove a better laboratory for nonleptonic physics if the experimental situation becomes clean enough.

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