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Abstract. Recent doubly Cabibbo suppressed decays of charmed pseudoscalar mesons are discussed and shown to imply the dominance of non spectator W-annihilation contributions. The calculation within a simple model supports this conclusion.

The recent experimental observations of doubly Cabibbo suppressed decays of the charmed pseudoscalar D^+ meson mark a real turning point in charm physics allowing us to study carefully the mechanism responsible for the differences between the lifetimes of D^0, D_s^+ and of D^+. In fact, the apparent lack of a substantial Branching Ratio (BR) for $D_s^+ \to \rho^0\pi^+$ can presumably account for the near equality of τ_{D^0} and $\tau_{D_s^+}$ **. On this ground it has been estimated that the overall contribution of all non-spectator decays of charmed pseudoscalar mesons should not exceed

** Due to color enhancement one would have guessed a larger contribution to D_s^+ than to D^0 from non spectator diagrams. This fact probably makes up for the some 20% of their total widths.

We will argue below that the recent experimental osbservations of doubly Cabibbo suppressed decays by E691 [1], WA-82 [2], and Mark-III [3] *i.e.*

$$BR(D^+ \to K^+\phi) = (3.3^{+1.8}_{-1.5} \pm 0.8) \quad 10^{-4} \tag{1}$$

$$\frac{BR(D^+ \to K^+K^-K^+)}{BR(D^+ \to K^-\pi^+\pi^+)} = 0.057 \pm 0.020 \pm 0.007 \tag{2}$$

$$BR(D^+ \to K^+\pi^-\pi^+) = 0.39 \quad ^{+0.09}_{-0.08} \quad ^{+0.09}_{-0.08}\ \% \tag{3}$$

can be understood if the so-called W-Annihilation (WA) contribution is the dominant one and, basically, provides the quasi totality of doubly Cabibbo suppressed decays.

A rather convincing argument that something outside the standard spectator contributions plays an important rôle can be given in the following way. Let us estimate how much the spectator diagrams contribute to doubly Cabibbo suppressed decays. To do this, we take the total D^+ width and multiply it by $(\sin\theta_C)^4$. This gives us about 0.3% which is, roughly, of the same order of magnitude of either one of eq.(2) or (3). Thus, this naive evaluation grossly underestimates (by several times and perhaps by as much as an order of magnitude) the actual rate of doubly Cabibbo suppressed decays.

At least two kinds of model have been proposed to solve this problem: both the so-called non-spectator models as well as the interference-type models are devised to produce some increase of the total rate of doubly Cabibbo suppressed decays (the first by allowing for some mechanism which makes non-zero the contribution

difference between τ_{D^0} and $\tau_{D_s^+}$ but the latter is not as large as originally people thought it was.

of non-spectator diagrams and the second due to all quarks in the final state having different flavors) and it is usually difficult to give arguments to select among them the correct mechanism. The large branching ratios found for the decays $D^+ \to K^+\phi$ and $D^+ \to K^+K^-K^+$ (~ 0.4), however, seem to give a rather clear cut answer to which among the two previous mechanisms is the most important one. Especially the second of these decays (which has no final state interaction and seems by far the largest one, compare Eqs.(1) and (2)), shows beyond any reasonable doubt that the non-spectator contributions (and among these the WA) must be almost entirely responsible for these doubly Cabibbo suppressed decays.

Let us analyze separately each of these reactions.

The decay $D^+ \to K^+\phi$ is the easiest to be understood. Its similarity with $D^0 \to \bar{K}^0\phi$ both in its weak vertex (both get contribution only from non-spectator diagrams, see Fig.1) as well as in its strong component (both have a final state in which a K and a ϕ are produced) allows us to write the following relationship between the two processes

$$\frac{BR(D^+ \to K^+\phi)}{BR(D^0 \to \bar{K}^0\phi)} = \frac{c_a^2}{c_e^2}\frac{\tau_{D^+}}{\tau_{D^0}}\frac{f_{D^+}^2}{f_{D^0}^2}(tg\theta_C)^4 \tag{4}$$

where c_a and c_e are the color factor for the quarks $u\bar{s}$ and $s\bar{d}$ produced in W-annihilation (WA) and in W-exchange (WE) respectively. Assuming, as usually done, $f_{D^+} \approx f_{D_0}$ and inserting the experimental values for τ_{D^+}, τ_{D^0} and θ_C, we get

$$\frac{BR(D^+ \to K^+\phi)}{BR(D^0 \to \bar{K}^0\phi)} \approx \frac{c_a^2}{c_e^2} \quad 0.006. \tag{5}$$

Using the naive parton model where in WA there are three times the number of degrees of freedom to produce a $q\bar{q}$ pair as compared with WE, using eq. (5) we have a good agreement between the various sets of experimental data. Differently stated, the E-691 result (eq.(1)), aside from giving a large value for the doubly Cabibbo suppressed decay $D^+ \to K^+\phi$ (comparable with the largest value estimated [4] for this kind of D^+ decay into a Vector and a Pseudovector [VP]), is quite well explained from the color degrees of freedom of a non-spectator WA diagram. Some authors [5] have suggested that final state interactions could be responsible for the decay $D^0 \to \bar{K}^0\phi$ in that they could increase its rate of production to values comparable to the most abundant D^+ decays into a VP system such as $D^0 \to K^-\rho^+$. Such an explanation, however, could not settle the $D^+ \to K^+\phi$ issue since its BR (eq(1)) would in this case necessitate a production rate an order of magnitude larger than those typical for a VP decay of the D^+ meson.

Going now to the decay $D^+ \to K^+K^-K^+$ observed experimentally by the WA-82 Collaboration (eq.(2)), also the nonresonant part of this process can proceed only through WA as shown in Fig.2; no final state interaction contributions can be invoked here *. As already mentioned, the experimental value for $D^+ \to K^+K^-K^+$ alone saturates the value expected from the naive parton model for all doubly Cabibbo suppressed decays. If a three-channel decay alone has this kind of BR, one can easily imagine that the sum of all doubly Cabibbo suppressed decays must add up to something about one order of magnitude larger than that of $D^+ \to K^+K^-K^+$. Stated differently, the total width of all doubly Cabibbo suppressed channels could easily add up to $\approx 1\%$ (or slightly more) of the total D^+ width.

The above conjecture is strengthened by the fact that the width measured by

* Notice that the resonant contribution in this reaction is only $\approx 10\%$ of the total as can be seen from the E-691 data just discussed. This appears rather strange given that the large bulk of known Cabibbo allowed D^+ decays is via a VP channel. This, however, applies only to those decays which come purely from spectator diagrams.

MARK-III for $D^+ \to K^+\pi^-\pi^+$ (eq(3)) is comparable to that for $D^+ \to K^+K^-K^+$ (eq.(2)). However, contrary to the two previous channels, $D^+ \to K^+\pi^-\pi^+$ receives contribution from the three distinct diagrams shown in Fig.3, *i.e.* WA, internal and external W-Radiation (WR). Barring the possibility of a large destructive interference in the Cabibbo allowed channel $D^+ \to K^-\pi^+\pi^+$, within the naive parton model one can roughly estimate the BR($D^+ \to K^+\pi^-\pi^+$) as coming from the two (simply) Cabibbo suppressed spectator contributions Fig. 3a,3b using the following approximation

$$BR(D^+ \to K^+\pi^-\pi^+)\,(tg\,\theta_C)^2 \approx 0.02.$$

Such a value is only $\approx 10\%$ of the total BR found experimentally for $D^+ \to K^+\pi^-\pi^+$ (eq.(3)) and this leads us to conclude that, so long as the interference mechanism is not the dominant one in the Cabibbo allowed sector, the largest contribution to the doubly suppressed mode can only come from WA. Such a conclusion is in keeping with the fact that the three-body decays $D^+ \to K^+\pi^-\pi^+$ and $D^+ \to K^+K^-K^+$ have approximately the same experimental widths (eqs.(2) and (3)).

Having established that the data point towards WA as the dominant non- spectator decay, it would now be nice to check theoretically this conjecture. For this we will resort to the general scheme developed some time ago to estimate non-spectator contributions to charm decay [6,7,8]. We may recall that as an application it was shown how the unexpectedly large two-body decay $D^0 \to \bar{K}^0\phi$ could be accomodated in such a scheme [9]. The fact that the decay is now a 3-body one, makes it impossible for us to repeat exactly this analysis. On the other hand, we can do something much simpler and unambiguous, namely, in a straightforward way we can use the technique of ref.[7] to estimate the *total* width expected within such a scheme for *all* doubly Cabibbo suppressed decays $D^+ \to u\bar{s}$ among which $D^+ \to K^+K^-K^+$

is, of course, just one (albeit one of the most important given that the resonant contribution into $K^+\phi$ is suppressed, as previously mentioned).

For details the interested reader is referred to the original literature, [7]. Here, we simply recall that the essence of this approach was the asumption that the wave function of the produced quark is given by a plane wave deformed by a gaussian, *i.e.*

$$\psi(\mathbf{x},t) = w\, exp(ix_\mu p_\mu)\, exp(-\mathbf{x}^2/2x_0^2). \tag{6}$$

The basic idea here is that of simulating in the simplest terms the fact that each produced quark can only be *free* as long as strong interaction effects are small. As soon as the quark has travelled some distance x_0 (*i.e.* the distance at which hadronization effects begin) the quark starts disappearing, *i.e.* its wave function begins to attenuate. Simple minded as such a picture may be, it accounts for a good deal of data and of experimental facts. One of the main consequences of such a scheme is that it enhances the contribution of the non-spectator diagrams as compared with the naive parton model expectations. Quite remarkably, this enhancement persists even in the approximation of zero-mass quarks. The total width calculated in this model for the WA contribution to D^+ decay has. for zero mass quarks the following expression [7]

$$\Gamma_{WA}(D^+ \to u\bar{s}) = \frac{1}{2}c_a^2 G^2 f_{D^+}^2 M_{D^+}^2 \{(2\pi M_{D^+}^2 x_0^2)^{-1} erf(x_0 M_{D^+}/\sqrt{2}) -$$

$$[(\pi^{3/2}\sqrt{2}M_{D^+}x_0)^{-1} + \sqrt{2}x_0 M_{D^+}/6\pi^{3/2}] exp(-\frac{1}{2}x_0^2 M_{D^+}^2)\}(tg\,\theta_C)^4 \tag{7}$$

where $erf(z)$ is the standard error function, c_a is the color factor (3 in our case) and f_{D^+} is the D^+ decay constant (which we take ≈ 0.2). For the length x_0 we take the value determined earlier [6-9] *i.e.* $x_0 \approx 0.2fm$. With these values of the parameters, from eq.(7) we get

$$\Gamma_{WA}(D^+ \to \text{``}u\bar{s}\text{''}) \approx 1.4 \times 10^{10} s^{-1}. \tag{8}$$

To get the estimate of the total width for D^+ decaying in doubly Cabibbo suppressed channels, we have to add to eq.(8) the spectator diagram contributions. This we can do easily (as an order of magnitude) by taking the total D^+ width multiplied by $(tg\,\theta_C)^4$ and we get $\approx 0.3 \times 10^{10}\, s^{-1}$. As a consequence, our expectation for the D^+ doubly Cabibbo suppressed decays is that they should represent $\approx 2\%$ of the total Γ_{D^+}. This value is much larger than expected within the naive parton model and is perfectly compatible with the experimentally measured BR (just consider that only the contributions from eqs.(1-3) add up to already nearly 0.7% of Γ_{D^+}).

The novel phenomenological information that comes from the recent measurements of doubly Cabibbo suppressed channels is, as we have shown, the large contribution of the WA component. This reactualizes the importance of non-spectator diagrams in the decays of charmed particles.

Several important questions remain open at this time such as i) how to account for the small difference between τ_{D^0} and $\tau_{D_s^+}$; ii) the smaller than expected $BR(D_s^+ \to \rho^0\pi^+)$ and, of course, iii) the actual computation of many body decay widths (*i.e.* either the extension of the model of ref.[7.8] to these problems or, more properly, the solution to the longstanding problem of hadronization). While the latter point will probably have to wait much longer before for truly reliable calculations, the advent of the new generation of high statistics experiments on charm decay opens the possibility of an accurate mapping of the various Cabibbo suppressed channels both for D^+ as well as for D^0 and D_s^+ which will, hopefully, allow a better quantitative understanding of their non-leptonic decays.

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Figure Captions

Fig.1 Spectator diagram contributions to $D \rightarrow K\phi$.

Fig.2 W-Annihilation contribution to $D^+ \rightarrow K^+K^-K^+$.

Fig.3 Contributions to $D^+ \rightarrow K^+\pi^-\pi^+$.

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FIG. 1

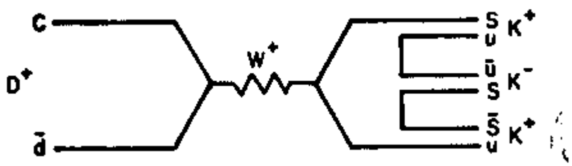

FIG. 2

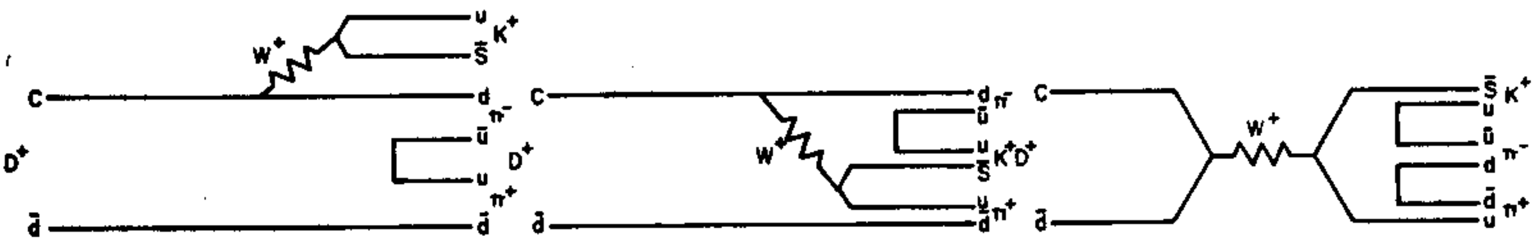

FIG. 3