A comment on hadronic charm decays

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Abstract

We give arguments in favor of the compatibility with standard physics of some large nonleptonic branching fractions in Cabibbo–forbidden $D^+$ decays, contrary to a recent claim in the literature.

More than twenty years ago, the large difference between the lifetimes of charged and neutral $D$ mesons has been attributed to the effect of the interference between color-favored and color-suppressed amplitudes in $D^+$ decays [1] and/or of the $W$-exchange contribution in the $D^0$ decay amplitudes [2]. Since the second explanation would imply (in its simplest form) a large annihilation contribution in $D^+_s$ and large branching ratios (BR’s) for unobserved decay channels, the interference is commonly believed to be the main effect [3]. Concerning exclusive decays, the surprisingly large BR for the decay $D^0 \to \bar{K}^0 \pi^0$ showed that the colour suppression is much less effective than expected [4, 5] in these decays. This fact may further point to important cancellations due to interference between color-allowed and color-(not-so-much)suppressed amplitudes in $D^+$ decays.

All the above applies to the (dominant) Cabibbo–allowed decays. In the Cabibbo–forbidden $D^+$ decays to two strange mesons, only the color-favored tree amplitude contributes (as it is also the case for $D^0$ decays in two charged particles). Therefore, the branching fractions for these decays might be considerably larger than what would be obtained with the simple-minded suppression by a factor $\tan^2 \theta_C$ with respect to Cabibbo–allowed decay rates. The same is true for the doubly–forbidden decays $D^+ \to K^{(*)+} X$. The precise values of these BR’s will however be affected by other effects, such as annihilation contributions and final state interactions ( rescattering), and are therefore very model-dependent.

In a recent letter, Close and Lipkin [6] suggested that the measured BR’s of the decays $D^+ \to K^{*+}\bar{K}^0$ ($3.1 \pm 1.4 \%$) [7] and $D^+ \to K^{*+}\bar{K}^{*0}$ ($2.6 \pm 1.1 \%$) [8], if confirmed with

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smaller error bars, may require "new physics" to explain them. We believe that this conclusion is not necessary.

In ref. \[6\] two points have been made: (a) the Cabibbo–forbidden branching ratios for \(D^0\) decays are \(< 0.4\%\), namely considerably smaller than the above–mentioned BR’s; (b) the Cabibbo–allowed \(D^+\) BR’s are instead not much larger. On the first point, we note that the ratio of lifetimes is \(\tau_{D^+}/\tau_{D^0} = 2.55 \pm 0.04\): therefore, for equal decay amplitudes, a \(D^+\) Cabibbo–forbidden BR of \(~ 1\%\) may be actually expected.

The second point is less clear–cut, due to the effect of interference in the decay amplitudes. Since interferences suppress both numerator and denominator in the BR in this case, a simplistic idea would attribute similar values for the BR of \(D^+\) and \(D^0\) in Cabibbo–allowed decays: this is at variance with the experimental data, since \(\text{BR}(D^0 \to \rho^+K^-) = 10.2 \pm 0.8 \%\) and \(\text{BR}(D^+ \to \rho^+\bar{K}^0) = 6.6 \pm 2.5 \%\). Another embarrassing fact is the considerable difference in the BR’s for \(D^+ \to K^+\bar{K}^0\) and \(D^+ \to K^{*+}\bar{K}^0\). Here hadronization effects are different, since in one case the virtual \(W^+\) gives rise to a pseudoscalar meson, in the other to a vector meson. In particular models, the data may (or may not) be reproduced.

Models that are able to describe the main features of the two-body \(D\) decay data without introducing any “new physics” have appeared in the literature \([9, 10, 11, 12]\) since a long time. They are generally based on a modified factorization approximation, in which the color suppression factor and annihilation and \(W\)-exchange contributions are determined by fitting some parameters to the experimental data. In the following, to give an example of a model where the BR for \(D^+ \to K^{*+}\bar{K}^0\) turns out to be large (1.52%), we present results from \([13]\). These were obtained making a fit with 15 parameters to all BR data for \(D\) decays in two pseudoscalar mesons (PP), a pseudoscalar and a vector meson (PV) and a pseudoscalar and a light scalar meson (PS) (corresponding to 56 experimental data points or upper bounds). Here, we will only discuss the fitted theoretical results for some particular decays, in order to illustrate the previous arguments. In particular, we will give results for decays to \(K^0\) and \(\bar{K}^0\) mesons separately, although in the fit decays in \(K_S\) were considered, since the neutral kaons are experimentally detected through their two pion decays.

The annihilation/\(W\)-exchange contribution in the factorized approximation (i.e. neglecting possible gluon emissions from the initial quarks) depends on the matrix element of the divergence of a vector (axial-vector) current for PP (PV) decays. This is transformed, using the equations of motion, to the matrix element of a scalar (pseudoscalar) density multiplied by the difference (sum) of quark masses. As a consequence, the annihilation contributions to Cabibbo–allowed \(D^+_s\) and to Cabibbo–forbidden \(D^+\) decays are quite small, being suppressed by light quark masses. Relevant annihilation contributions are present instead for Cabibbo–forbidden \(D^+_s\) and doubly–Cabibbo–forbidden \(D^+\) decays.

The pattern arising for the factorized amplitudes may be strongly mixed up by final state interactions. In this model, all the states belonging to the same representation of

\[3\] It may be noted that 6.6 \pm 2.5 \% is compatible, within two standard deviations, both with 3.1 \pm 1.4 \% (\(D^+\) Cabibbo–suppressed, a surprise) and with 10.2 \pm 0.8 \% (\(D^0\) Cabibbo–allowed, as roughly expected).
the flavor SU(3) symmetry mix among themselves. The rescattering is dominated by the nearby resonances, whose experimental masses and widths (when known) determine the phase-shifts.

The results of the fit for some \( D^+ \) decay channels of interest are presented in Table 1. In the first column we list the branching ratios that would result prior to rescattering corrections (BR\(_{\text{NR}}\)) – not a fit to the data. The second column contains the final, rescattered results (BR\(_{\text{RR}}\)). In the third column we write the present experimental data [15] that in some cases differ from the data that were fitted.

Table 1: Branching ratios (in \%) for some nonleptonic decays of \( D^+ \) mesons.

| \( D^+ \rightarrow \) | BR\(_{\text{NR}}\) | BR\(_{\text{RR}}\) | BR\(_{\text{exp}}\) |
|-----------------|----------------|----------------|----------------|
| \( \pi^+ K^0 \) | 2.939          | 2.939          | —              |
| \( \pi^+ \pi^0 \) | 0.185          | 0.185          | 0.25±0.07      |
| \( K^+ K^0 \)   | 1.486          | 0.764          | 0.58±0.06      |
| \( K^+ \pi^0 \)  | 0.083          | 0.055          | —              |
| \( K^0 \pi^+ \)  | 0.057          | 0.053          | —              |
| \( \pi^+ K_S \)  | 1.088          | 1.347          | 1.38±0.09      |
| \( \rho^+ K^0 \) | 14.076         | 12.198         | —              |
| \( \pi^+ K^0 \)  | 0.076          | 1.996          | 1.92±0.19      |
| \( \rho^+ \pi^0 \) | 0.775          | 0.451          | —              |
| \( \pi^+ \rho^0 \) | 0.012          | 0.104          | 0.104±0.018    |
| \( \phi \pi^+ \)  | 0.505          | 0.619          | 0.61±0.06      |
| \( K^+ K^0 \)   | 0.653          | 0.436          | 0.42±0.05      |
| \( K^0 K^0 \)   | 0.096          | 0.057          | —              |
| \( K^+ \rho^0 \)  | 0.012          | 0.029          | 0.025±0.012    |
| \( K^0 \rho^+ \)  | 0.062          | 0.027          | 0.036±0.016    |
| \( K^0 \rho^+ \)  | 0.001          | 0.042          | —              |
| \( \rho^+ K_S \)  | 6.946          | 5.820          | 3.30±1.25      |

The left part of Table 1 refers to PP decays. We note that the two Cabibbo–forbidden decays have very different BR\(_{\text{NR}}\)’s: this is due to the interference between “tree” and “color–suppressed” amplitudes, present in the \( \pi^+ \pi^0 \) case (as well as in the Cabibbo–allowed decay to \( \pi^+ K^0 \)) and absent for the \( K^+ K^0 \) decay, which has therefore a much larger BR. A similar argument also applies to the doubly–forbidden decays, that do not have interference and have instead possibly large annihilation contributions; their BR’s are of the order of \( \tan^2 \theta_C \) BR\(_{\text{NR}}\)(\( D^+ \rightarrow K^+ K^0 \)) and much larger than \( \tan^4 \theta_C \) BR\(_{\text{NR}}\)(D\(^+ \rightarrow \pi^+ K^0 \)). The rescattering effects are quite big, and approximately half of the biggest Cabibbo–forbidden BR is redistributed to the other channels, namely \( \pi \eta \) and \( \pi \eta' \).

In the right part of Table 1, it can be noted that the naturally paired channels \((V_i P_j \) and \( P_i V_j)\) have very different BR’s. The simplest case to analyze is the \( K^{*+} K^0 \) and \( K^+ K^{*0} \) pair, with no interference and a very small annihilation contribution. In the factorized approximation, the first decay is induced by the \( VV \) part of the effective hamiltonian, the second by the \( AA \) part. The parameters entering in the calculation favor the first

\(^4\)A similar treatment of final state interactions has been recently presented in [14]. However, in that paper the phase shifts have been erroneously multiplied by a factor of two.
contribution, the main reason being the ratio of decay constants \( f_{K^*} / f_K \simeq 1.4 \); final state interactions further enhance this effect. When also interference enters the game, the smaller BR’s may be almost completely cancelled, as it happens for the Cabibbo–allowed case. The rescattering effects are not very big for the channels having large BR_{NR}, while they obviously change a lot the smallest ones. The general pattern is however rather stable.

The results of the fit for some \( D_s^+ \) decay channels of interest are presented in Table 2. Again, our comments refer to the results prior to rescattering corrections, listed in the first and fourth columns. It is to be noted that the branching ratios in final states containing a hypothetical \( s\bar{s} \) pseudoscalar meson with the \( \eta \) mass would be approximately twice the values reported in the first row in Table 2, with the value for the \( \eta - \eta' \) mixing angle that we use [16].

Table 2: Branching ratios (in %) for some nonleptonic decays of \( D_s^+ \) mesons.

| \( D_s^+ \to \) | BR_{NR} | BR_{RR} | BR_{exp} | \( D_s^+ \to \) | BR_{NR} | BR_{RR} | BR_{exp} |
|----------------|---------|---------|----------|----------------|---------|---------|----------|
| \( \pi^+\eta \) | 5.026   | 1.131   | 1.7\pm0.5 | \( \rho^+\eta \) | 9.182   | 8.122   | 10.3\pm3.2 |
| \( \pi^+\phi \) | 5.065   | 4.552   | 3.6\pm0.9 | \( \pi^+\phi \) | 5.065   | 4.552   | 3.6\pm0.9 |
| \( K^0K^+ \) | 3.285   | 4.623   | —        | \( K^0K^+ \) | 4.108   | 4.812   | 3.3\pm0.9 |
| \( \pi^+K^0 \) | 1.099   | 0.373   | < 0.8    | \( \rho^+K^0 \) | 0.847   | 1.288   | —        |
| \( \pi^0K^+ \) | 0.211   | 0.146   | —        | \( \pi^+K^* \) | 0.898   | 0.445   | 0.65\pm0.28 |
| \( K^+\eta \) | 0.003   | 0.300   | —        | \( \omega K^+ \) | 0.288   | 0.178   | —        |
| \( K^+K^0 \) | 0.012   | 0.012   | —        | \( \pi^0K^* \) | 0.177   | 0.076   | —        |
| \( K_SK^+ \) | 1.450   | 2.473   | 1.80\pm0.55 | \( K_SK^* \) | 0.704   | 1.096   | 2.15\pm0.70 |

We comment at first on the PP decays. A comparison of the color–favored decays (into \( \pi^+\eta, \pi^+K^0 \) and \( K^+K^0 \)) shows that the ratios of Cabibbo–forbidden and doubly–Cabibbo–forbidden to the Cabibbo–allowed BR are, respectively, about 0.1 and 0.001, instead of the expected values (\( \tan^2 \theta_C \simeq 0.05 \) and \( \tan^4 \theta_C \simeq 0.003 \)); this may be explained as the effect of a rather large annihilation contribution in the Cabibbo–forbidden decay, \( D_s^+ \to \pi^+K^0 \), and of an important interference in the doubly–Cabibbo–forbidden channel. Similar arguments hold for the color–suppressed decays. A discussion of the final state \( K^+\eta \) would be more involved, since also the non-strange components of the \( \eta \) meson participate in this decay.

In the decays to PV final states, as it was noted for the \( D^+ \), those induced by the \( VV \) part of the effective Hamiltonian are larger than the others in the Cabibbo–allowed and
doubly–forbidden cases. The Cabibbo–forbidden and color–favored decays \( D_s^+ \to \rho^+ K^0 \) and \( D_s^+ \to \pi^+ K^* \) are roughly equally frequent, as a consequence of large annihilation contributions, equal and opposite \(^5\) in these two channels. The annihilation terms are also responsible of the big difference among the Cabibbo–forbidden and color–suppressed decays \( D_s^+ \to \rho^0 K^+, \omega K^+ \) and \( \pi^0 K^{*+} \). The rescattering corrections are often quite large, and the pattern discussed above is somehow hidden in the final results. However, it must be said that the general quality of the fit for \( D_s^+ \) decays is not very good, for example the prediction for \( D_s^+ \to \rho^+ \eta' \) is \( \text{BR}_{NR(RR)} = 2.52 (2.46) \% \) against an experimental value \( 12\pm4 \% \). It may well be that some surprise will come out from new \( D_s^+ \) data, once better statistical and systematical accuracy is attained.

| \( D^0 \to \) | BR\(_{NR}\) | BR\(_{RR}\) | BR\(_{exp}\) |
|------------|-----------|-----------|-----------|
| \( \pi^+ K^- \) | 5.114 | 3.847 | 3.80±0.09 |
| \( \bar{K}^0 \pi^0 \) | 0.711 | 1.310 | — |
| \( K^+ K^- \) | 0.579 | 0.424 | 0.412±0.014 |
| \( K^0 \bar{K} \) | 0.0 | 0.130 | 0.071±0.019 |
| \( \pi^+ \pi^- \) | 0.500 | 0.151 | 0.143±0.007 |
| \( \pi^0 \pi^0 \) | 0.052 | 0.115 | 0.084±0.022 |
| \( K^+ \pi^- \) | 0.048 | 0.033 | 0.015±0.02 |
| \( K^0 \pi^0 \) | 0.007 | 0.008 | — |
| \( K_S \pi^0 \) | 0.428 | 0.759 | 1.14±0.11 |

Table 3: Branching ratios (in %) for some nonleptonic decays of \( D^0 \) mesons.

In Table 3 we have reported for completeness the data and predictions for some exclusive \( D^0 \) decays. Comments analogous to those given on the other Tables could be made, in particular concerning the large differences between \( K^{*+} K^- \) and \( K^+ K^{*-} \), as well as between \( \rho^+ \pi^- \) and \( \pi^+ \rho^- \), which are rather softened by rescattering effects. We

\(^5\) The opposite sign arises from the F–type coupling of the pseudoscalar density.
Table 4: Inclusive branching ratios (in %) for two-body decays of $D$ mesons.

| Decay          | CA      | CF      | DCF     | Ratio   | Ratio   |
|----------------|---------|---------|---------|---------|---------|
| $D^0 \rightarrow PP$ | 8.71±0.38 | > 0.68  | 0.057   | > 0.075 | 0.18    |
|                | 7.34    | 1.31    | 0.057   |         | 0.043   |
| $D^0 \rightarrow PV$ | 25.4±1.2 | > 0.44  | 0.085   | > 0.02  | 0.12    |
|                | 23.0    | 2.68    | 0.085   |         | 0.032   |
| $D^+ \rightarrow PP$ | 2.77±0.18 | > 1.43  | 2.10    | > 0.44  | 0.71    |
|                | 2.94    | < 2.56  | 0.164   | < 0.92  | 0.078   |
| $D^+ \rightarrow PV$ | 8.5±2.5 | > 2.6   | 0.205   | > 0.24  |         |
|                | 14.2    | 3.35    | 0.205   |         |         |
| $D^+_s \rightarrow PP$ | 9.2±1.6  | 11.2    | 0.012   | 0.12    | 0.009   |
|                | 11.2    | 1.31    | 0.012   |         |         |
| $D^+_s \rightarrow PV$ | 32.4±4.6 | 25.1    | 0.024   | 0.094   | 0.010   |
|                | 25.1    | 2.37    | 0.024   |         |         |

Note moreover that final state interactions are essential to allow the decays into a pair of strange neutral mesons [17, 18].

It may be of some interest to consider partially inclusive rates of Cabibbo–allowed (CA), forbidden (CF) and doubly–forbidden (DCF) decay processes. For such quantities the comparison of experimental data with theoretical predictions are much less dependent on the rescattering corrections. Their ratios may then be compared with the appropriate power of $\tan\theta_C$ to check if the simple–minded suppression ($\text{CF/CA}\simeq 2 \tan^2\theta_C$ and $\text{DCF/CF}\simeq 0.5 \tan^2\theta_C$) gives an adequate description of the data. This is illustrated in Table 4, that we now comment upon.

The success of the theoretical model in describing the data is generally acceptable. The worst case is given by the Cabibbo–allowed $D^+ \rightarrow PV$ decays, where the theoretical predictions are considerably larger than experiment.

Concerning the inclusive data and theoretical predictions for $D^0$ decays, the simple–minded suppression referred to above is a consequence of (flavor) SU(3) symmetry. In the limit of total decoupling of the third quark family, the weak effective hamiltonians form a U-spin triplet, the $D^0$ meson has zero U-spin and therefore one has only one decay amplitude [13, 20]. Moreover, the annihilation contributions to decays into PP vanish for CF, are SU(3) violating and of opposite sign for CA and DCF, while they are nonvanishing and SU(3) allowed for decays to PV. These features give a reasonable explanation of the results for the ratios, both bigger than naively expected in PP decays and near to the naive expectations in PV decays.

The charged and charmed mesons form a U-spin doublet. As a consequence, even in the
symmetric limit, we have two independent decay amplitudes, and one would recover the simple-minded suppression factors only if these two amplitudes were equally important. More generally, SU(3) symmetry would predict the following relations

\[
\left(\frac{\text{CF}}{\text{CA}}\right)_{D^+} \cdot \left(\frac{\text{DCF}}{\text{CF}}\right)_{D^+_s} = \left(\frac{\text{CF}}{\text{CA}}\right)_{D^+_s} \cdot \left(\frac{\text{DCF}}{\text{CF}}\right)_{D^+} = \tan^4 \theta_C ,
\]

both for PP and for PV final states. From Table 4 one obtains for the three terms in the above equation the numerical results (0.0064, 0.0094, \(\tan^4 \theta_C = 0.0026\)) for PP decays and (0.0024, 0.0057, 0.0026) for PV decays. This shows that the flavour symmetry is rather badly broken in this factorized model, without any need of “new physics”.

The inclusive data of \(D^+\) show once more that the ratio CF/CA is much larger than the (very) naive expectation, due to destructive interference in the Cabibbo–allowed amplitudes. This is particularly evident for the decays into PP, although no single branching fraction is larger than 1%. The ratio DCF/CF is also larger than expected, due to the annihilation contribution in DCF.

The predictions for \(D^+_s\) inclusive decays (the data are still too sparse to give indications) suggest that, while CF/CA is “normal”, the ratio DCF/CF is smaller than naively expected, due to interference effects in DCF.

Decays in two vector mesons are not included in this fit, so that we are not able to present a theoretical estimate of the other large BR(\(D^+ \rightarrow K^{*+}K^{*0}\)).

In this paper, we have shown that in a model for \(D\) decays based on (generalized) factorization and including resonance–mediated final state interactions it is possible to get a branching ratio for the Cabibbo–forbidden channel \(D^+ \rightarrow K^{*+}K^{0}\) of about 1.52 % versus an experimental value of 3.1±1.4 % (in fact, an even larger prediction for this BR was given in a previous version of the model \([11]\) prior to the experimental result). On the other hand, the theoretical prediction for the Cabibbo–allowed decay BR(\(D^+ \rightarrow \rho^+ K_S\)) is 5.82 % versus the experimental result 3.30±1.25 % (the other Cabibbo–allowed decay is well reproduced). Within the present, large error bands this is compatible: for the ratio of the two BR’s we have 0.26 (theory) versus 0.94±0.55 (experiment). While the central values undeniably disagree, the discrepancy may be alleviated not only by a much smaller BR(\(D^+ \rightarrow K^{*+}K^{0}\)), but also by a somewhat larger BR(\(D^+ \rightarrow \rho^+ K_S\)): this is the direction to which a model using factorization and no extreme “new physics” hypothesis would point.

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