Final State Interactions, Resonances and CP Violation in D and B Exclusive Decays

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Abstract

Hadron resonances affect nonexotic $D^o$ decays but not $B$ decays which are far from the resonance region. We obtain new information from exclusive decays and show that interference between colour favoured and colour suppressed diagrams is constructive in $B$ and (some) $D$ decays in contrast to the inclusive decays where a net Pauli destructive interference is claimed. We suggest that a systematic study of $B$ decay final states containing excited mesons such as $a_1 D$ or $\pi D^{**}$ show opposite behaviour for $B^o$ and $B^+$ relative to the ground state channels. We give inequalities...
among final state branching ratios for several $B$ and $D$ channels. Decays into $\pi K^{(*)}$ and $\rho K^{(*)}$ appear to show different behaviours.
1 Introduction

The role of final state interactions and possible hadron resonances in weak decays of heavy flavour hadrons remains to be understood, particularly in view of the presence of known meson resonances in the vicinity of the D mass\cite{1,2}. In the present paper we look for clues to possible resonance effects in the systematics of decay branching ratios.

We first note that the final states of Cabibbo-favored dominant decay modes of charged $D$ and charged $B$ decays have the exotic isospin quantum number $I = 3/2$ which does not exist for the quark-antiquark system. There are therefore no meson resonances contributing to these final states. The corresponding neutral $D$ and neutral $B$ decays have final states with nonexotic isospin $I=1/2$ as well as the exotic $I=3/2$ and can have resonance contributions. It is therefore of interest to look for differences in the systematics of charged and neutral decays. Note that the isospin couplings of corresponding $D$ and $B$ decay diagrams are identical, since they differ only in interchanging the two isoscalar transitions $c \to s$ and $b \to c$.

One immediately finds that the neutral and charged $D$ lifetimes are different but that neither the semileptonic partial widths for $D$ decays nor the total $B$ widths show such a difference. This suggests that meson resonances are responsible for speeding up the hadronic decays of the $D^\circ$ while such effects can be absent at the $B$ mass which is far above the resonance region. We also note that the theoretical basis of the $\Delta I = 1/2$ rule in kaon decays still is not fully understood and that the $I = 2$ state of the two-pion system which is suppressed by $\Delta I = 1/2$ also has exotic isospin. There is also the unexplained enhancement of nonleptonic weak decays relative to semileptonics. There seems to be a general enhancement of weak decays into mesonic final states having nonexotic quantum numbers relative to those having exotic quantum numbers and also relative to semileptonic decays.

Before rushing to explain everything with final state resonances, we note that other explanations have been proposed for the $D$ lifetime difference\cite{3}. The $W$-exchange weak diagram, in which a $W$ boson is exchanged between the initial quark-antiquark pair exists only for the neutral initial states and provides an extra $I=1/2$ contribution. There are arguments suggesting a mass dependence for this diagram which suppresses this contribution at the $B$ mass. There have also been arguments pointing out that the two possible colour couplings, generally called colour favored and colour suppressed, lead to the same final state in charged decays; e.g. $K^+\pi^o$ and lead to different final states; e.g. $K^+\pi^-$ and $K^o\pi^o$ in neutral decays. Thus in the charged decays the two amplitudes can interfere destructively in what has been called a “Pauli” effect thereby suppressing them relative to the neutral decays.

The explanations using these weak diagrams are still subject to intense controversy\cite{4}. The sums over final states to obtain decay rates use a quark basis and neglect all details of hadron spectroscopy such as the nature of the low-lying hadronic final states which have the largest phase space. This phase space factor dominates the $K_L - K_S$ lifetime difference and there are suggestions that similar effects determine the lifetime difference of the $B_s$ eigenstates\cite{5,6}. Furthermore the mass dependence and the sign of the “Pauli” interference have been questioned. In order to obtain additional input from experiment to help resolve these questions we investigate what can be learned from exclusive decay modes, where there are a wealth of data constantly becoming available and where new systematics beyond what is available in inclusive decays can give new clues to the underlying mechanisms.

In sections 2 and 3 we present a preliminary detailed analysis of the decays to the
lowest-lying exclusive quasi-two-body final states which shows that the nonexotic I=1/2
collection is enhanced in D decays (section 2) but not in B decays (section 3) as ex-
pected either from a resonance argument or from W exchange with some mass factor. This
enhancement is seen in the nonexotic exclusive D decays as well as in the lifetime difference.
The systematics of B decays are in marked contrast to this; not only is there no enhance-
ment of the non-exotic exclusive B decays but one finds that the exotic transitions are
enhanced relative to the nonexotics! This indication for constructive interference between
colour favored and colour suppressed contributions to the exotic final states (rather than
destructive as suggested by the Pauli argument) is also supported by our analysis of the
exclusive D decays (section 4).

This raises the interesting point\[7\] that this exotic enhancement of the exclusive B decays
to low lying final states (e.g. πD) would contradict the observed absence of enhancement
in the inclusive decays indicated by the approximate equality of the charged and neutral
lifetimes. This suggests that there are form factor effects depending upon final state wave
functions for decays into higher states (e.g. φD, πD∗) which reverse the relative signs of
the colour favored and colour suppressed contributions to different final states. We comment
on this in section 5.

Our analysis uses the language of the weak parton model but is based on a much more
general flavour-topology formulation which includes all final state interaction effects\[8\]. A
heavy-flavoured quark and a light-flavoured antiquark are assumed to enter a black box
from which two final q\bar{q} pairs emerge. The initial nonstrange quark line is assumed to
travel in all possible complicated paths going forward and backward in time and emitting
and absorbing gluons until it either disappears in the box by interaction in a weak vertex
(W) or emerges from the box as a constituent of the final charmed or strange meson (T)
or as a constituent of the final nonstrange meson (S). Since all strong interactions are
assumed to conserve isospin, the additional q\bar{q} pair created by gluons within the box in
the W topology must be isoscalar, and the contributions to the T and S diagrams must be
independent of the isospin of the initial nonstrange quark which travels through the box
undergoing only isospin-invariant strong interactions. The familiar parton model colour
favoured, colour suppressed and W diagrams are a particular example of this more general
topological classification.

## 2 A Systematic Enhancement of Nonexotic $D^o$ Decays

As a first step it is interesting to compare the experimental branching ratios for $D^+$ to exotic
I=3/2 states with the corresponding branching ratios of $D^o$ to charged and neutral final
states which are mixtures of I=3/2 and I=1/2 and therefore have a non-exotic component.
Note that the exotic I=3/2 $D^+$ amplitudes have both colour-favored and-colour suppressed
amplitudes, while the $D^o$ amplitudes to charged final states are purely colour-favored and
the $D^o$ amplitudes to neutral final states are purely colour suppressed. To enable focusing
on systematics in comparing decays to different final states with different wave functions
and form factors, we note that the color-favored tree amplitudes should have a point-like
form factor e.g. the wave function at the origin, for the charged nonstrange meson and a
hadronic form factor for the strange meson nearly the same as that for the semileptonic
decay to the same strange meson. We therefore use this semileptonic branching ratio
for normalization and express the errors separately for the hadronic numerator and the
semileptonic denominator.
• For the exotic $\pi^+K^o$ final state we obtain:

\[
\frac{br(\pi^+K^o)}{br(\nu e^+K^o)} = 0.42 \pm 0.04 \pm 13\%
\]  

(1a)

in comparison with the nonexotic colour-favored and colour-suppressed

\[
\frac{br(\pi^+K^-)}{br(\nu e^+K^-)} = 1.05 \pm 0.04 \pm 6\%; \quad \frac{br(\pi^oK^o)}{br(\nu e^+K^-)} = 0.54 \pm 0.07 \pm 6\%
\]  

(1b)

• For the exotic $\rho^+K^o$ final state we obtain:

\[
\frac{br(\rho^+K^o)}{br(\nu e^+K^o)} = 1.0 \pm 0.37 \pm 13\%
\]  

(2a)

in comparison with the nonexotic colour-favored and colour-suppressed

\[
\frac{br(\rho^+K^-)}{br(\nu e^+K^-)} = 2.74 \pm 0.34 \pm 6\%; \quad \frac{br(\rho^oK^o)}{br(\nu e^+K^-)} = 0.29 \pm 0.05 \pm 6\%
\]  

(2b)

\[
\frac{br(\omega K^o)}{br(\nu e^+K^-)} = 0.53 \pm 0.11 \pm 6\%
\]  

(2c)

• For the exotic $a_1(1260)^+K^o$ final state we obtain:

\[
\frac{br(a_1(1260)^+K^o)}{br(\nu e^+K^o)} = 1.23 \pm 0.25 \pm 13\%
\]  

(3a)

in comparison with the nonexotic colour-favored and colour-suppressed

\[
\frac{br(a_1(1260)^+K^-)}{br(\nu e^+K^-)} = 2.08 \pm 0.31 \pm 6\%; \quad \frac{br(a_1(1260)^oK^o)}{br(\nu e^+K^-)} < 0.13
\]  

(3b)

• For the exotic $\pi^+K^*(892)^o$ final state we obtain:

\[
\frac{br(\pi^+K^*(892)^o)}{br(\nu e^+K^*(892)^o)} = 0.47 \pm 0.09 \pm 10\%
\]  

(4a)

in comparison with the nonexotic colour-favored and colour-suppressed

\[
\frac{br(\pi^+K^*(892)^-)}{br(\nu e^+K^*(892)^-)} = 3.8 \pm 0.46 \pm 23\%; \quad \frac{br(\pi^oK^*(892)^o)}{br(\nu e^+K^*(892)^-)} = 2.30 \pm 0.23 \pm 23\%
\]  

(4b)

• For the exotic $\rho^+K^*(892)^o$ final state we obtain:

\[
\frac{br(\rho^+K^*(892)^o)}{br(\nu e^+K^*(892)^o)} = 0.43 \pm 0.28 \pm 10\%
\]  

(5a)

in comparison with the nonexotic colour-favored and colour-suppressed

\[
\frac{br(\rho^+K^*(892)^-)}{br(\nu e^+K^*(892)^-)} = 4.54 \pm 0.18 \pm 23\%; \quad \frac{br(\rho^oK^*(892)^o)}{br(\nu e^+K^*(892)^-)} = 1.23 \pm 0.31 \pm 23\%
\]  

(5b)

There appears to be a systematic enhancement of the nonexotic $D^o$ decays relative to the exotic $D^+$ decays described by exactly the same leading diagrams.
3 Exotic-Nonexotic Systematics of B Decays

For B decays treated by analogy with the foregoing D decays, we find a radically different systematics. First we list the modes by analogy with the D decays in section 2.

• For the exotic $\pi^+\bar{D}^o$ final state we obtain:

$$\frac{br(\pi^+\bar{D}^o)}{br(\nu e^+\bar{D}^o)} = 0.33 \pm 0.03 \pm 44\%$$

(B1a)

in comparison with the nonexotic colour-favored and colour-suppressed

$$\frac{br(\pi^+D^-)}{br(\nu e^+D^-)} = 0.16 \pm 0.02 \pm 26\%; \quad \frac{br(\pi^o\bar{D}^o)}{br(\nu e^+D^-)} \leq 0.02 \pm 26\% \leq 0.025$$

(B1b)

• For the exotic $\rho^+\bar{D}^o$ final state we obtain:

$$\frac{br(\rho^+\bar{D}^o)}{br(\nu e^+\bar{D}^o)} = 0.83 \pm 0.11 \pm 44\%$$

(B2a)

in comparison with the nonexotic colour-favored and colour-suppressed

$$\frac{br(\rho^+D^-)}{br(\nu e^+D^-)} = 0.41 \pm 0.07 \pm 26\% \quad \frac{br(\rho^oD^o)}{br(\nu e^+D^-)} \leq 0.04$$

(B2b)

$$\frac{br(\omega\bar{D}^o)}{br(\nu e^+D^-)} \leq 0.05(?$$

(B2c)

• For the exotic $a_1(1260)^+\bar{D}^o$ final state we obtain:

$$\frac{br(a_1(1260)^+\bar{D}^o)}{br(\nu e^+\bar{D}^o)} = 0.31 \pm 0.25 \pm 44\%$$

(B3a)

in comparison with the nonexotic colour-favored and colour-suppressed

$$\frac{br(a_1(1260)^+D^-)}{br(\nu e^+D^-)} = 0.31 \pm 0.17 \pm 26\% \quad \frac{br(a_1(1260)^o\bar{D}^o)}{br(\nu e^+D^-)} < ???$$

(B3b)

• For the exotic $\pi^+D^{*-}$ final state we obtain:

$$\frac{br(\pi^+\bar{D}^{*-})}{br(\nu e^+\bar{D}^{*-})} = 0.08 \pm 0.01 \pm 33\%$$

(B4a)

in comparison with the nonexotic colour-favored and colour-suppressed

$$\frac{br(\pi^+D^{*-})}{br(\nu e^+D^{*-})} = 0.06 \pm 0.01 \pm 11\% \quad \frac{br(\pi^o\bar{D}^{*-})}{br(\nu e^+D^{*-})} < 0.03$$

(B4b)

• For the exotic $\rho^+\bar{D}^{*-}$ final state we obtain:

$$\frac{br(\rho^+\bar{D}^{*-})}{br(\nu e^+\bar{D}^{*-})} = 0.23 \pm 0.05 \pm 33\%$$

(B5a)

in comparison with the nonexotic colour-favored and colour-suppressed

$$\frac{br(\rho^+D^{*-})}{br(\nu e^+D^{*-})} = 0.17 \pm 0.03 \pm 11\% \quad \frac{br(\rho^o\bar{D}^{*-})}{br(\nu e^+D^{*-})} < 0.03$$

(B5b)

In contrast to D decays where there appears to be a systematic enhancement of the nonexotic $D^o$ decays relative to the exotic $D^+$ decays described by exactly the same leading diagrams, here we find the exotic modes tend to be slightly larger than the non-exotic. There is also a drastic suppression of the non-exotic colour suppressed.
4 A Weak Diagram Analysis

There are two different approaches to the nonexotic enhancement present in $D$ decays. One is to attribute it to strong final state interactions in channels having resonances\cite{10,11}. However there are also attempts to explain it via weak interaction diagrams without taking final state interactions into account\cite{8,9}. Both approaches explain the absence of such enhancement in $B$ decays, but the “reverse enhancement” of exotics noted above in low-lying exclusive $B$ decays has not previously been discussed.

In the weak interaction approach there are three types of contributions to these Cabibbo-favored $D$ decays in the standard model: (1) a colour-favored tree diagram; (2) a colour-suppressed tree diagram; (3) a W-exchange diagram. We use this formalism but interpret results using the general flavour-topology approach described in the introduction. Both tree diagrams contribute to the exotic channels but the W-exchange diagram does not contribute since it goes via an intermediate state containing only a single $q\bar{q}$ pair. In the nonexotic channels there are W-exchange contributions and either a colour-favored or colour-suppressed diagram, but not both. The argument then goes that there is an enhancement in the non-exotic channels due to the W-exchange diagram, and there is a suppression in the exotic channels due to so-called “Pauli” interference between the colour-favored and colour-suppressed diagrams, which is claimed to be always destructive\cite{8}. This claim, however, is based on general arguments that apply to inclusive $D$ decays and whether it is correct and whether it applies universally to all exclusive channels is open to question and to experimental tests.

As a first test to see how this can work, we express the the amplitudes for the vector-pseudoscalar decay modes in terms of these three contributions denoted by $T$, $S$ and $W$ respectively for colour-favored tree, colour-suppressed tree and W exchange. Note that any contribution due to final state interactions which go via an intermediate $q\bar{q}$ state is pure $I = 1/2$ and has exactly the same couplings to all decays as the $W$ contribution\cite{8}. Thus our analysis below is completely general and includes these final state and resonance contributions. However we cannot determine at this stage how much of the $W$ contribution is due to weak W exchange and how much is due to strong final state enhancements; e.g.

resonances.

\begin{align}
A_D(\rho^+ \bar{K}^0) &= T + S, & A_B(\rho^+ \bar{D}^0) &= T_B + S_B, \quad (6a) \\
A_D(\rho^+ K^-) &= T + W, & A_B(\rho^+ D^-) &= T_B + W_B, \quad (6b) \\
A_D(V_u \bar{K}^0) &= S, & A_B(V_u \bar{D}^0) &= S_B, \quad (6c) \\
A_D(V_d \bar{K}^0) &= W, & A_B(V_d \bar{D}^0) &= W_B, \quad (6d) \\
A_D(\rho^0 \bar{K}^0) &= \frac{1}{\sqrt{2}} \cdot (S - W), & A_B(\rho^0 \bar{D}^0) &= \frac{1}{\sqrt{2}} \cdot (S_B - W_B), \quad (6e) \\
A_D(\omega \bar{K}^0) &= \frac{1}{\sqrt{2}} \cdot (S + W), & A_B(\omega \bar{D}^0) &= \frac{1}{\sqrt{2}} \cdot (S_B + W_B), \quad (6f) \\
A_D(\phi \bar{K}^0) &= \xi W & A_B(\phi \bar{D}^0) &= \xi W_B \quad (6g)
\end{align}

where we have used the notation $V_u$ and $V_d$ for the $u\bar{u}$ and $d\bar{d}$ vector meson states and noted that the $\rho^0$ and $\omega$ are equal mixtures of these two states with opposite relative phase. $\xi$ is a flavour-SU(3)-breaking parameter expressing the suppression of creating strange quark pairs from the vacuum. We do not use $A(\phi \bar{K}^0)$ in our subsequent analysis since it adds one
piece of data with one free parameter. The parameter $\xi$ can be determined from experiment if desired just to check internal consistency.

At this stage we have four experimental quantities expressed in terms of three complex amplitudes and therefore in terms of five parameters. But we can get a qualitative picture if we simply assume that all amplitudes are relatively real. We now have four quantities overdetermining three parameters and we can see whether these can fit the data.

### 4.1 Application to $D \to \rho K$ Decays

We find that the data can indeed be fit by setting

$$T = 0.81 \quad (7a)$$
$$W = 0.87 \quad (7b)$$
$$S = 0.17 \quad (7c)$$

where we have normalized the amplitudes so that

$$\frac{br(\rho^+ \bar{K}^0)}{br(\nu e^+ \bar{K}^0)} = 1.0 \pm 0.37 \pm 13\% = (T + S)^2 = 0.96 \quad (8a)$$
$$\frac{br(\rho^+ K^-)}{br(\nu e^+ K^-)} = 2.74 \pm 0.34 \pm 6\% = (T + W)^2 = 2.82 \quad (8b)$$
$$\frac{br(\rho^0 \bar{K}^0)}{br(\nu e^+ \bar{K}^0)} = 0.29 \pm 0.05 \pm 6\% = (1/2) \cdot (W - S)^2 = 0.25 \quad (8c)$$
$$\frac{br(\omega \bar{K}^0)}{br(\nu e^+ \bar{K}^0)} = 0.53 \pm 0.11 \pm 6\% = (1/2) \cdot (W + S)^2 = 0.54 \quad (8d)$$

We note the following qualitative feature of this fit. The colour-favored tree and the W-exchange amplitudes are roughly equal and the colour-suppressed tree amplitude is much smaller. The interference between the colour-favored and the colour-suppressed tree amplitudes is constructive in the exotic $\rho^+ \bar{K}^0$ decay, in contradiction with the "Pauli effect" which predicts destructive interference.

The basic physics in this qualitative argument lies in relative phases determined by the isospinology and the experimental result that

$$|A(\rho^0 \bar{K}^0)| = \frac{1}{\sqrt{2}} \cdot |(S - W)| < |A(\omega \bar{K}^0)| = \frac{1}{\sqrt{2}} \cdot |(S + W)| \quad (9)$$

This tells us that the interference between the $S$ and $W$ amplitudes for $A(\rho^0 \bar{K}^0)$ must be destructive. Thus with the phase convention chosen for eqs. (6) the experimental result (9) requires positive relative phase for the $S$ and $W$ amplitudes.

The tree amplitudes for the $\rho - K$ final states have the same phase when the flavour of the spectator quark is changed since the change of the spectator quark is an isospin raising or lowering operator.

The W-exchange amplitudes have the opposite phase for the charged and neutral $\rho$ decays because they arise from an $I = 1/2 \, q \bar{q}$ state. The creation of an additional nonstrange pair by gluons conserves isospin, and the isospin Clebsches for coupling the $I=1 \, \rho$ with the $I=1/2$ kaon to a total isospin of $I=1/2$ have opposite relative phase for the charged
and neutral modes. The physics of the negative Clebsch is simple. When a spin of 1/2 is coupled to a spin of 1, the two spins can be either parallel or antiparallel. When they are parallel the total spin is 3/2. To make a total spin of 1/2 the individual spins must be antiparallel. This gives the negative phase.

These arguments determine uniquely the relative phases in eqs. (6). The T-S interference in $\rho^+ K^0$ and the T-W interference in $\rho^+ K^-$ are thus required to be the same; i.e. either both constructive or both destructive. Note that the $\rho - \omega$ mixing of $\bar{u}d$ and $\bar{d}u$ states plays a crucial role in this analysis and allows the relative phase of the $W$ and $S$ amplitudes to be determined by the experimental inequality (9).

These features tend to support the picture of resonance enhancement in the nonexotic channels. In this picture the $W$ amplitude has a contribution from final-state rescattering, which has the same topology as the $W$ exchange. Thus the prominent $W$ amplitude may be largely due to final state resonance scattering.

The relative phase of the $T$ and $S$ amplitudes can in principle be calculated from the standard model and hadron wave functions for the mesons. This is a complicated calculation involving point-like and hadronic form factors for the $\rho$ and $K$ mesons and colour and spin recouplings. These complications are avoided in the calculations for inclusive processes where the arguments for the “Pauli relative phase” may be valid. The present exclusive process can certainly not be described as a simple Pauli effect. We have avoided this calculation by using the experimental inequality (9) as input. A correct calculation of the relative phase would predict this inequality and hopefully would agree with experiment.

### 4.2 Application to $B \rightarrow XD$ Decays

In the $B \rightarrow XD$ Decays where $X$ denotes any isovector meson, detailed analyses analogous to those above for $D$ decays are presently masked by the large error bars, but the improvements anticipated from $B$-factories and elsewhere should enable sharper quantification soon. However, it is already clear from the small upper bounds on the decays into two neutral particles that both the $W_B$ and $S_B$ amplitudes are small. We can therefore analyze the data using expressions to lowest order in these small amplitudes. It is convenient to define:

\[
\Gamma^+ \equiv |A_B(X^+ D^0)|^2 = |T_B + S_B|^2 \approx T_B^2 + 2T_B \cdot S_B, \tag{10a}
\]

\[
\Gamma^+ \equiv |A_B(X^+ D^-)|^2 = |T_B + W_B|^2 \approx T_B^2 + 2T_B \cdot W_B, \tag{10b}
\]

\[
\Gamma^{oo} \equiv |A_B(X^0 \bar{D}^0)|^2 = \frac{1}{2} \cdot |(S_B - W_B)|^2. \tag{10c}
\]

Then to lowest order in the small amplitudes,

\[
\frac{1}{4} \cdot \frac{|\Gamma^+ - \Gamma^-|^2}{\Gamma^+ + \Gamma^-} \approx \frac{|T_B \cdot (S_B - W_B)|^2}{2T_B^2} = \Gamma^{oo} \cos^2 \theta \tag{11a}
\]

where

\[
\cos \theta \equiv \frac{T_B \cdot (S_B - W_B)}{|T_B||S_B - W_B|} \tag{11b}
\]

The present data show only upper bounds for $\Gamma^{oo}$ which satisfy these relations for all the $XD$ states given above in eqs. (B1-B5).

However, these data already reveal the interesting and surprising systematics that for $B$ decays the exotic branching ratios are consistently larger than the nonexotic and that this
difference comes from an interference term between the $T$ and $W - S$. The direct terms proportional to squares of these small amplitudes are seen from the data to be below the presently measured upper limits. Although in principle the relation (11) does not specify which of the two small amplitudes dominates in the interference term, it seems hardly likely that the $W$ amplitude should have opposite phase in $D$ and $B$ decays (i.e. that it would be constructive in $D$ and destructive in $B$ decays). One rather assumes that just as in $D$ decays the colour-suppressed amplitude is small, but interferes constructively with the colour-favored amplitude. This completely disagrees with the conventional weak diagram folklore, where this “Pauli” interference is predicted to be destructive in both cases.

Thus we see that in contrast to the $D$ decays where

$$W_D \geq T_D > S_D$$  \hspace{1cm} (12a)

the $B$ system shows

$$T_B > S_B >> W_B.$$  \hspace{1cm} (12b)

It is interesting to note that these results are at least qualitatively in accord with expectations from the presence of direct channel resonance enhancements. However it is not surprising that the $W$-exchange goes away. The weak interaction calculators say that this results naturally from mass factors in the diagram.

### 5 Comparison of $B$ and $D$ Decays

For a ball-park estimate set $T=3$, $W=3$, and $S=1$ for $D$ decays and the same with $W=0$ for $B$ decays. These values are not normalized; only ratios are relevant. We then obtain for the ratios:

$$\frac{\Gamma_{D}^{+}}{\Gamma_{D}^{-}/\Gamma_{D}^{0}} = 4 : 9 : \frac{1}{2}$$ \hspace{1cm} (13a)

for $D$ decays and

$$\frac{\Gamma_{B}^{+}}{\Gamma_{B}^{-}/\Gamma_{B}^{0}} = 16 : 9 : \frac{1}{2}$$ \hspace{1cm} (13b)

for $B$ decays.

This is clearly oversimplified, since there is no reason to believe that all amplitudes are relatively real. But the qualitative prediction that the exotic branching ratios are systematically lower than the decays into two charged particles by a factor of two in $D$ decays and systematically higher by a factor of two for $B$ decays is impressive.

There is also the qualitative feature that a small colour-suppressed amplitude can give a significant enhancement to the exotic amplitude by constructive interference, while its direct contribution to the neutral decay is down by an order of magnitude.

An interesting contrast between $B$ and $D$ decay systematics in the above analysis has been pointed out by Yuval Grossman\[7\]. In $D$ decays the systematic enhancement of decay rates in nonexotic channels is seen in total decay rates; the lifetime of the neutral $D$ being shorter than the charged $D$. In the $B$ system there is no such overall enhancement; the lifetimes are equal at the level of experimental errors. Thus the “reverse enhancement” observed in the $B$ decays and which are as large as factors of two favoring the charged modes cannot be general. It is very likely that if there are only the $T$ and $S$ amplitudes, the relative phase must depend upon hadron wave functions and probably reverse with higher excitations, such as $P$-waves or radial excitations of $S$-waves.
We may see this already in the case of the $a_1 D$ (eqns B3) where unfortunately the statistics are not good enough to prove anything. There are also further tantalising hints in the $B$ system if one assumes that the $\pi^+ \pi^+ \pi^-$ accompanying the $D^*$, with mass between 1.0 and 1.6GeV, is dominated by the $a_1^+$. The central values of the data superficially suggest that here is a final state where the charged exotic is suppressed relative to the all charged non-exotic. However, as previously, the errors are such to prevent any meaningful conclusion.

In both examples involving the $a_1$ production, the $T$ amplitude depends on the point-like coupling of the $a_1$ (wave function at the origin) and an overlap integral of the $B$ and $D$ ground states. The $S$ amplitude by contrast depends upon the point-like coupling of the $D$ (due to the short range $W$ exchange between the $c$ and $\bar{d}$) and a $p$-wave matrix element between the $B$ and $a_1$ ground states. Thus the wavefunction overlaps and the relative phase of the two amplitudes for a final state with one $s$-wave meson and one $p$-wave meson could well be opposite to that for a final state with two $s$-wave mesons.

If this is the case one might expect to see a similar effect in charm decays. Current data on the $a_1 K$ channel are not good enough to decide. The possibility that the interference sign is channel dependent may be tested also by data on scalar mesons in $D$ final states, such as the $K_0(1430)$ and the broad $f_0(1300)$ which are candidate members of the scalar nonet. Data exist on $D^+ \to \pi^+ K_0^*(1430)$, $D^o \to \pi^+ K_0^+(1430)$; in the absence of data on $K_0^{*+}\pi^o$ one may use $f_0(1300)\bar{K}^0$ as the flavour and overall spin structures are the same. If one demands that the $S$ amplitude is colour suppressed in magnitude relative to the $T$ amplitude, then these channels involving scalar mesons appear to prefer destructive interference.

Further hints that the interference may be destructive in the $D \to \pi K^*$ channels comes from their Cabibbo suppressed analogues

$$br(D^+ \to \pi^+ K^{o*}) \sim (T + S)^2 = 2.2 \pm 0.4\%$$

from which if we ignore modifications arising from phase space and exclusive form factors (which tend to counterbalance\cite{12}), we may expect

$$br(D^+ \to \pi^+ \rho^o) \sim \frac{(T + S)^2}{2} \times sin^2\theta \sim 0.05\%$$

(where we have ignored any annihilation or Penguin contribution). This is consistent with the data which report $< 0.15\%$ for this Cabibbo suppressed mode and suggests this analysis is robust. Then if we consider the related Cabibbo suppressed mode

$$br(D^+ \to \phi \pi^+) \sim S^2 sin^2\theta = 0.67 \pm 0.08\%$$

we have a rather clean measure of the strength of the colour suppressed $S$ diagram. This suggests that the $\rho \pi$ rate is “small” due to $T$ and $S$ interference being destructive (or that there is destructive interference with a $W$ or Penguin topology). The $TS$ destructive interference would also suggest that the $\pi^+ \bar{K}^{o*}$ also is “small” due to destructive interference (which is consistent with the analysis of section 2.1 applied to eqns.(4)).

The systematics of constructive and destructive interference appear from our analysis to be non trivial and channel dependent. The data need to be sharpened as we have noted if a pattern is to be discerned.

Elsewhere\cite{11} it has been noted that the $\pi(1.8)$ can contribute to the direct channel in penguin driven Cabibbo suppressed $D$ decays. The existence of this state is well established
though its internal structure, whether hybrid or radial excitation, remains to be settled. In either case one expects that there will be a $K$ partner and with a mass $K(\sim 1.9)$. Such a state will have typical strong decay width of $O(200\text{MeV})$ and thereby overlap the D mass; consequently it may be expected to affect the $0^{-+}$ overall final states in D decays via the $W$-exchange diagram.

Analogously, enhancements may be anticipated in the $0^{++}$ overall due to the presence of the (radial excitation) $K_0(1950); \Gamma \sim 200$, and possibly Cabibbo suppressed modes by its $f_0$ or $a_0$ partners.

This is in sharp contrast to the B decays where the required resonances would be $J^P = 0^-$ or $0^+$ D states around the B mass, namely $\sim 5\text{GeV}$. Unlike the $K$ and $\pi$ system where the lightest hybrids or prominent radial excitations are expected around $2\text{Gev}$ and hence in the vicinity of the (initial state) $D$ meson, the lightest hybrids or prominent radial excitations of the $D$ with $0^-$ or $0^+$ quantum numbers are anticipated to be in the $\sim 3.5\text{GeV}$ region, far below the $5\text{GeV}$ mass of the (initial state) $B$ meson.

If this is an important source of the D decay $W$ enhancement, one may expect correlation between those channels and the branching ratios of the respective $K$ direct channel resonances. In particular it will require the $I = \frac{1}{2}$ correlation among charged and neutral modes in the final state. This appears to be satisfied for $\pi K$ and within errors for $\pi K^*$; it may also be true (possibly) for $\rho K^*$ (when one compares the transverse polarization values for the latter as these are the only two that enable direct comparison in a single experiment in the PDG). It does not arise for the $a_1 K$ and $\rho K$ where the all neutral modes are much suppressed relative to their charged counterparts.

## 6 Some Sum Rules for Insight from D and B Decay Data

The relations (6) satisfy the sum rule

$$A(\rho^+ K^o) = A(\rho^+ K^-) - \sqrt{2} \cdot A(\rho^0 K^o)$$

This sum rule is seen to follow from general isospin relations. Both sides are pure $I = 3/2$ amplitudes. They are related because the initial state has $I = 1/2$ and the weak interaction operator for these $c \to s$ transitions is pure $I = 1$. In this form the sum rule relates only the exotic contributions; i.e. colour-favored and colour-suppressed, and projects out all W exchange and resonance contributions. Since phases are unknown, this sum rule gives only a triangular inequality for the experimental branching ratio data. It is interesting that for this case the data are:

$$\frac{\sqrt{\{br(\rho^+ K^-)\}}}{\sqrt{\{br(\nu e^+ K^-)\}}} = 1.66 \pm 0.11 \pm 3\% \quad \sqrt{2} \cdot \frac{\sqrt{\{br(\rho^0 K^o)\}}}{\sqrt{\{br(\nu e^+ K^-)\}}} = 0.76 \pm 0.07 \pm 3\%$$

(15a)

$$\frac{\sqrt{\{br(\rho^+ K^o)\}}}{\sqrt{\{br(\nu e^+ K^o)\}}} = 1.0 \pm 0.18 \pm 6.5\%$$

(15b)

Then

$$\frac{\sqrt{\{br(\rho^+ K^-)\}}}{\sqrt{\{br(\nu e^+ K^-)\}}} - \sqrt{2} \cdot \frac{\sqrt{\{br(\rho^0 K^o)\}}}{\sqrt{\{br(\nu e^+ K^-)\}}} = 0.90 \pm 0.21 \pm 7\%$$

(15c)
which is within experimental errors of the lower limit of the inequality.

A similar approach can be made for $\rho \bar{K}^*$ final states using the data in section 2. From these we find that the sum rules with pions in the final state both have equal contributions to the sum rule from the two legs of the triangle for the neutral decay modes, as if the neutral decays were pure $I=1/2$. The exact significance of this behavior is unclear without information on phases. But the fact that both pion sum rules show similar behavior and both $\rho$ sum rules show similar behavior and the behavior of pionic and $\rho$ sum rules are very different from one another may be significant.

On the other hand the final state interactions and possible resonances are expected to be very different for the even parity (scalar) and odd parity (pseudoscalar) states since strong interactions conserve parity. The two pion sum rules which show similar behavior refer to two states of opposite parity and the two $\rho$ sum rules which show similar behavior probably also refer to states of opposite parity. In the vector-vector case both parities are present but two of the three helicity amplitudes have even parity whereas the single vector-pseudoscalar amplitude has odd parity.

It will be interesting to see if these results hold up under improved statistics and, if so, a challenge to explain them.

The analogous sum rule for $B$ decays is more conveniently rearranged to the form

$$A(\rho^+ \bar{D}^o) - A(\rho^+ D^-) = -\sqrt{2} \cdot A(\rho^o \bar{D}^o)$$  \hspace{1cm} (B14)

In this form the sum rule is seen to cancel the $T$ contribution on the LHS and to give two expressions for the combination $S - W$, which we have seen from the data to be small. For this case, the sum rule provides the same information as the relation (B11).

The relevant data are:

$$\frac{\sqrt{\{br(\rho^+ D^-)\}}}{\sqrt{\{br(\nu e^+ D^-)\}}} = 0.64 \pm 0.05 \pm 13\% \quad \sqrt{2} \cdot \frac{\sqrt{\{br(\rho^o \bar{D}^o)\}}}{\sqrt{\{br(\nu e^+ D^-)\}}} < 0.28 \quad (B15a)$$

$$\frac{\sqrt{\{br(\rho^+ \bar{D}^o)\}}}{\sqrt{\{br(\nu e^+ D^-)\}}} = 0.91 \pm 0.06 \pm 22\% \quad (B15b)$$

The upper limit on the RHS is seen to be very near to the lower bound on the LHS. Thus better data will be able to determine the relative phase of the contributing amplitudes, defined by the angle $\theta$ in eq. (11).

A similar approach gives the analogous sum rule for the $\rho \bar{D}^* \pi \bar{D}$ and $\pi \bar{D}^*$ final states.

In the $D$ decays to $\pi \bar{K}^*(\bar{K})$ the data were suggestive that the neutral decays were dominated by $I = 1/2$. This is not the case for $B^o \to \pi D$ though this is not ruled out for the $B^o \to \pi \bar{D}^*$.

### 7 Conclusions - Possible Implications for CP Searches

We have shown interesting systematics in exclusive $D$ and $B$ decays which warrant future experimental investigation and theoretical analysis.

One example of possible new systematics would be CP-exotic states which like flavour-exotic states also cannot arise in the quark-antiquark system and cannot be enhanced by $q\bar{q}$ resonances. However, such states may exist in a quark-antiquark-gluon configuration, which can be produced by a W-exchange diagram. There might also be as yet unknown hybrid
$q\bar{q}G$ states in this region with CP-exotic quantum numbers. Therefore it is of interest to look for such final states.

We now note that a better understanding of decay systematics can prove useful in guiding the choice of useful candidate decay modes for CP-violation studies. Many proposed searches for CP violation focus on producing $B\bar{B}$ pairs at the $\Upsilon(4S)$ and observing a lepton asymmetry in one decay when the other is observed to decay into a CP eigenstate like $\psi K_S$. Unfortunately there are not many known unambiguous CP eigenstates. Many final states like $\rho\pi$ have several partial waves with opposite CP eigenvalues. Such states can be used in CP violation experiments only if the two partial waves (and thereby the $CP = \pm 1$ combinations) have been separated by partial wave or isospin analysis. These analyses would be completely unnecessary if decay systematics show that only partial waves with a given CP eigenstate are present. If, for example only the odd CP partial waves appear in the $3\pi$ final state, all neutral three-pion states could be used in CP-violation experiments by analogy with $\psi K_S$ without any necessity for the selection of $\rho - \pi$ mass peak and isospin analyses. This would occur if decays into CP-exotic partial waves were suppressed.

There are two $J^{PC}$ values allowed for the weak decay of a spin-zero meson into a neutral $3\pi$ state; namely $0^{--}$ and $0^{-+}$. Of these the $0^{--}$ is CP even and has exotic quantum numbers while the $0^{-+}$ is CP odd and has normal quantum numbers. It is therefore of interest to examine the $3\pi$ final states in $D$ and $B$ decays by Dalitz plots and partial wave analyses using charged as well as neutral decays. Preliminary data on $D_s$ decays into three pions [10] suggest dominance by CP-odd partial waves.

Since the parity-violating weak interaction leads to final states that overall can be both scalar and pseudoscalar, the resonance structures at the $D$ and $D_s$ masses can be quite different for the states of opposite parity. This could show up as a systematic difference.

Note that nonleptonic enhancement in nonexotic channels as well as large W-exchange contributions are inconsistent with factorization. It is believed that factorization is a good approximation at sufficiently high mass. An interesting open question is whether and where a transition between nonleptonic enhancement and factorization occurs.

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