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PHYSICS LETTERS B

Physics Letters B 405 (1997) 157–167

Final-state interactions, resonances and CP violation in D and B exclusive decays

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Received 23 July 1996; revised manuscript received 21 March 1997

Editor: P.V. Landshoff

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PHYSICS LETTERS B

Aims and Scope
Physics Letters B ensures the rapid publication of letter-type communications in the fields of Nuclear Physics/Intermediate Energy Physics, High Energy Physics and Field Theory.

Abstracted/indexed in:
Current Contents: Physical, Chemical & Earth Sciences; INSPEC.

Subscription Information 1997
PHYSICS LETTERS A (ISSN 0375-9601) and PHYSICS LETTERS B (ISSN 0370-2693) will each be published weekly. For 1997 13 volumes, volumes 224–236 (78 issues altogether) of Physics Letters A have been announced. For 1997 26 volumes, volumes 390–415 (104 issues altogether) of Physics Letters B have been announced. The subscription prices for these volumes are available upon request from the Publisher. PHYSICS REPORTS (ISSN 0370-1573) will be published approximately weekly. For 1997 14 volumes, volumes 277–290 (84 issues altogether) of Physics Reports have been announced. The subscription price for these volumes is available upon request from the Publisher.
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U.S mailing notice – Physics Letters B (ISSN 0370-2693) is published weekly by Elsevier Science B.V., P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Annual subscription price in the USA is US$ 6917.00 (valid in North, Central and South America only), including air speed delivery. Periodicals postage paid at Jamaica, NY 11431.
USA POSTMASTERS: Send address changes to Physics Letters B, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.
AIRFREIGHT AND MAILING in the USA by Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.

⊚ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands

North-Holland, an imprint of Elsevier Science

17 July 1997

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Abstract

Systematics of experimental partial widths for corresponding charged and neutral decays into low-lying *exclusive* quasi-two-body final states in the same isospin multiplets are analyzed. Exclusive and inclusive D decays both show enhancement of neutral relative to charged decays. Exclusive charged B decays show an unexplained enhancement in low-lying channels absent in inclusive decays which must be reversed in other channels in order to equalise the charged and neutral lifetimes. The charged B exclusive enhancement arises from constructive interference between colour favored and colour suppressed contributions in those exclusive channels where all final state mesons have nodeless wave functions. This analysis directs the experimental search to modes involving excited mesons like the a_1 where the relative phase which depends upon hadron form factors can be reversed whereby the charged-B enhancement may be reversed. © 1997 Elsevier Science B.V.

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 [1,2]. Recent progress in B decay FSI [3–7] has been summarized in an analysis [8] pointing out [5] that soft FSI may not disappear in the large m_B limit and may be significant in hadronic B decays. Sizable inelastic charge-exchange rescattering effects in $B^0 \to \pi^0 \bar{D}^0$ have also been calculated [6] using a Regge approach.

The Cabibbo-favored dominant decay modes of charged D and charged B decays have no meson resonance contributions since their final states have the exotic isospin quantum number $I = 3/2$. The corresponding neutral D and B decays have final states with both non-exotic isospin $I = 1/2$ and exotic $I = 3/2$ and can have resonance contributions. 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 $b \to c$.

The necessity to include FSI in weak decays has long been recognized [9]. Bauer, Stech and Wirbel

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[2] Work supported in part by the European Community Human Capital Mobility program "Eurodafne", Contract CHRX-CT92-0026.

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[4] Work supported in part by the German-Israeli Foundation for Scientific Research and Development (GIF).

PII S0370-2693(97)00596-0

[10] define effective four-fermion interactions which include some FSI in their four-point vertices. The effective annihilation diagram in their Fig. 2 includes a FSI rescattering which is exactly a Harari-Rosner duality diagram [12,13]. In this duality approach Regge exchanges are dual to resonances and contributions from exchange degenerate Regge trajectories cancel in exotic channels and tend like resonances to enhance the $I = 1/2$ transitions in D and B decays. This further supports an approach of trying to apply pre-QCD knowledge of strong-interaction dynamics and hadron spectroscopy to final state interactions in weak decays.

The reasonable agreements obtained in overall analyses of the complete set of available data [10,14] leave some fine points and puzzles for further investigation. The role of interference effects between dominant and smaller amplitudes in providing clues to CP violation and possible new physics has been pointed out [15] with particular emphasis on the role of interference effects that occur naturally in the wave functions of flavor-mixed neutral mesons.

In this context we note that final states like $\phi\pi$ and $\phi\rho$ are topologically forbidden in duality diagrams (OZI rule), while they are colour-favored for D_s decays in the dominant spectator diagram. The colour-suppressed $K^*\bar{K}$ and $K^*\bar{K}^*$ decays are topologically allowed, and can be enhanced by the "BSW Fig. 2" diagram. This could explain the absence of colour suppression in the experimental data in strong disagreement with BSW predictions. Many subsequent attempts to improve on BSW have been continuously confounded by the violation of predictions by new surprising data; e.g. the unexpected strong $D_s \to \rho\eta'$ and $\pi\omega$ decays. This again supports the original conjecture that interference effects provided by neutral flavour-mixed mesons can offer clues to new physics. We leave further consideration of D_s decays for a subsequent paper when more data become available.

Here we examine the systematics of sets of *exclusive* nonstrange D and B decays involving final state mesons in the same isospin multiplets and flavor-mixed neutral mesons. The availability of better data on such sets of decays provide an opportunity for exploring finer interference effects, since many uncertainties in final state interactions and hadronic form factors are common to the set of decays and tend to cancel. We find evidence for interesting physics at the interface between weak interactions and hadron spectroscopy suggesting further experimental and theoretical investigation.

In contrast to other treatment we do not calculate diagrams from strong interaction models. We consider the contributions from the diagrams a, b and c of Fig. 2.4 of Chau [11] or Fig. 1 of BSW as phenomenological parameters to be determined by experiment. They are denoted respectively, as T, S and W: convenient mnemonics for diagrams which reduce respectively to the conventional colour-favored tree, colour-suppressed tree and W-exchange weak diagrams in the absence of strong interactions. We use known symmetry and topological properties of strong interactions to relate the values of these parameters in different decays which differ only by the flavours of their constituent quarks.

Our general flavour-topology amplitudes [16] are equivalent to the 1a, 1b and 1c amplitudes in BSW with their four-point effective interaction vertices generalized to include all possible initial and final state strong interactions. A heavy-flavoured quark and a non-strange antiquark are assumed to enter a black box from which two final $q\bar{q}$ pairs emerge. The initial nonstrange antiquark line travels in all possible 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 in the W topology must be isoscalar, and the contributions to the T and S diagrams must be independent of the I_z of the initial nonstrange quark which travels through the box undergoing only isospin-invariant strong interactions. We furthermore use the relation between the quark structures of the ρ and ω mesons to obtain relations going beyond conventional isospin relations [15].

The neutral and charged D lifetimes are different but neither the semileptonic partial widths for D decays nor the total B widths show such a difference. This suggests that meson resonances might be responsible for speeding up the hadronic decays of the D^0 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 non-exotic quantum numbers relative to those having exotic quantum numbers and also relative to semileptonic decays.

Other explanations proposed for the D lifetime difference [14] suggest destructive interference in what has been called a "Pauli" effect between colour favored and colour suppressed contributions to charged decays. In neutral decays these contributions are incoherent as they lead to different final states; e.g. $K^+\pi^-$ and $K^0\pi^0$ and the W-exchange weak diagram absent in charged decays provides an extra $I = 1/2$ contribution. Some arguments suggest a mass dependence which suppresses this diagram at the B mass. These explanations are still subject to intense controversy [18]. 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 [19,20]. 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 non-exotic $I = 1/2$ contribution is enhanced in D decays (Section 2) but not in B decays (Section 3) as expected either from a resonance argument or from W exchange with some mass factor. This enhancement is seen in the non-exotic 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 enhancement of the non-exotic exclusive B decays but one finds that the exotic transitions are enhanced relative to the non-exotics! 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 exotic enhancement of the exclusive B decays to low lying final states (e.g. πD) while no enhancement is observed in inclusive decays [17] suggests the existence of form factor effects depending upon final state wave functions for decays into higher states (e.g. $a_1 D$, πD^{**}) which can reverse the relative signs of the colour favored and colour suppressed contributions to different final states. We comment on this in Section 5.

2. A systematic enhancement of non-exotic D^0 decays

As a first step we compare experimental branching ratios for D^+ to exotic $I = 3/2$ states with corresponding branching ratios of D^0 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 (CF) and colour-suppressed (CS) amplitudes, while the D^0 amplitudes to charged and neutral final states are respectively purely colour-favored and purely colour suppressed.

Table 1 shows the experimental data. To enable focusing on systematics in comparing decays to different final states with different wave functions and form factors, we note that the colour-favored tree amplitudes should have a point-like form factor (e.g. the wave function at the origin), for the charged nonstrange meson, while the hadronic transition form factor for $D \to K^{(*)}$ will be similar to that for the semileptonic decay to the corresponding strange meson. We therefore use this semileptonic branching ratio for normalization and express the errors separately for the hadronic numerator and the semileptonic denominator.

3. Exotic-non-exotic systematics of B decays

For B decays treated by analogy with the foregoing D decays, we find a radically different systematics. The experimental data are shown in Table 2.

Table 1
Systematic of exotics and non-exotic D decays

Exotic $D^+ \to M^+\bar K^{(*)0}$	Non-exotic – CF $D^0 \to M^+K^{(*)-}$	Non-exotic – CS $D^0 \to M^0\bar K^{(*)0}$
$\frac{br(\pi^+\bar K^0}{br(\nu e^+\bar K^0)}$ $0.42 \pm 0.04 \pm 13\%$	$\frac{br(\pi^+K^-)}{br(\nu e^+K^-)}$ $1.10 \pm 0.03 \pm 5\%$	$\frac{br(\pi^0\bar K^0)}{br(\nu e^+K^-)}$ $0.61 \pm 0.06 \pm 5\%$
$\frac{br(\rho^+\bar K^0)}{br(\nu e^+\bar K^0)}$ $1.0 \pm 0.37 \pm 13\%$	$\frac{br(\rho^+K^-)}{br(\nu e^+K^-)}$ $3.10 \pm 0.30 \pm 5\%$	$\frac{br(\rho^0\bar K^0)}{br(\nu e^+K^-)}$ $0.35 \pm 0.05 \pm 5\%$
		$\frac{br(\omega\bar K^0)}{br(\nu e^+K^-)}$ $0.60 \pm 0.12 \pm 5\%$
$\frac{br(a_1(1260)^+\bar K^0)}{br(\nu e^+\bar K^0)}$ $1.23 \pm 0.25 \pm 13\%$	$\frac{br(a_1(1260)^+K^-)}{br(\nu e^+K^-)}$ $2.10 \pm 0.32 \pm 5\%$	$\frac{br(a_1(1260)^0\bar K^0)}{br(\nu e^+K^-)}$ < 0.55
$\frac{br(\pi^+\bar K^*(892)^0)}{br(\nu e^+\bar K^{*0})}$ $0.41 \pm 0.04 \pm 10\%$	$\frac{br(\pi^+K^*(892)^-)}{br(\nu e^+K^{*-})}$ $2.5 \pm 0.2 \pm 16\%$	$\frac{br(\pi^0\bar K^*(892)^0)}{br(\nu e^+K^{*-})}$ $1.54 \pm 0.20 \pm 16\%$
$\frac{br(\rho^+\bar K^*(892)^0)}{br(\nu e^+K^{*0})}$ $0.43 \pm 0.28 \pm 10\%$	$\frac{br(\rho^+K^*(892)^-)}{br(\nu e^+K^{*-})}$ $2.98 \pm 0.19 \pm 16\%$	$\frac{br(\rho^0\bar K^*(892)^0)}{br(\nu e^+K^{*-})}$ $0.73 \pm 0.16 \pm 16\%$

There appears to be a systematic enhancement of the non-exotic D^0 decays relative to the exotic D^+ decays described by exactly the same leading diagrams.

Table 2
Systematics of exotic and non-exotic beauty decays.

Exotic $B^+ \to M^+\bar D^{(*)0}$	Non-exotic – CF $B^0 \to M^+D^{(*)-}$	Non-exotic – CS $B^0 \to M^0\bar D^{(*)0}$
$\frac{br(\pi^+\bar D^0)}{br(\nu e^+\bar D^0)}$ $0.33 \pm 0.03 \pm 44\%$	$\frac{br(\pi^+D^-)}{br(\nu e^+D^-)}$ $0.16 \pm 0.02 \pm 26\%$	$\frac{br(\pi^0\bar D^0)}{br(\nu e^+D^-)}$ $\leqslant 0.02 \pm 26\% \leqslant 0.025$
$\frac{br(\rho^+\bar D^0)}{br(\nu e^+\bar D^0)}$ $0.83 \pm 0.11 \pm 44\%$	$\frac{br(\rho^+D^-)}{br(\nu e^+D^-)}$ $0.41 \pm 0.07 \pm 26\%$	$\frac{br(\rho^0\bar D^0)}{br(\nu e^+D^-)}$ $\leqslant 0.04$
		$\frac{br(\omega\bar D^0)}{br(\nu e^+D^-)}$ $\leqslant 0.05$ (?)
$\frac{br(a_1(1260)^+\bar D^0)}{br(\nu e^+\bar D^0)}$ $0.31 \pm 0.25 \pm 44\%$	$\frac{br(a_1(1260)^+D^-)}{br(\nu e^+D^-)}$ $0.31 \pm 0.17 \pm 26\%$	$\frac{br(a_1(1260)^0\bar D^0)}{br(\nu e^+D^-)}$ $<$???
$\frac{br(\pi^+\bar D^{*0})}{br(\nu e^+\bar D^{*0})}$ $0.10 \pm 0.01 \pm 15\%$	$\frac{br(\pi^+D^{*-})}{br(\nu e^+D^{*-})}$ $0.06 \pm 0.01 \pm 6\%$	$\frac{br(\pi^0\bar D^{*0})}{br(\nu e^+D^{*-})}$ < 0.03
$\frac{br(\rho^+\bar D^{*0})}{br(\nu e^+\bar D^{*0})}$ $0.29 \pm 0.05 \pm 15\%$	$\frac{br(\rho^+D^{*-})}{br(\nu e^+D^{*-})}$ $0.16 \pm 0.03 \pm 6\%$	$\frac{br(\rho^0\bar D^{*0})}{br(\nu e^+D^{*-})}$ < 0.03

In contrast to D decays where there appears to be a systematic enhancement of the non-exotic D^0 decays relative to the exotic D^+ decays described by exactly the same leading diagrams, here we find the exotic modes tend to be larger than the non-exotic. There is also a drastic suppression of the non-exotic colour suppressed.

This leads immediately to an interesting paradox pointed out by Yuval Grossman [17]. The same decay rate systematics seen above in exclusive decays is also seen in total D decay widths $\Gamma_{tot}(D^\pm) < \Gamma_{tot}(D^0)$, but not in total B decay widths $\Gamma_{tot}(B^\pm) \approx \Gamma_{tot}(B^0)$. Thus the "reverse enhancement" observed in the low-lying exclusive B decays favoring the charged modes by factors of two cannot be general and must be compensated by opposite enhancements in other exclusive modes. This suggests a dependence on hadron wave functions which warrants further investigation and is discussed below.

4. A phenomenological diagram analysis of vector-pseudoscalar decays

We now consider in detail the $D \to \bar K V$ and $B \to \bar D V$ decay modes where V denotes a ρ or ω. We first note that all models express the amplitudes for these decay modes in terms of the T, S and W contributions defined above. That there are only these three can be seen by noting that there are only three possible ways to produce the final kaon in $D \to \bar K V$. The strange quark produced by the decay of the charmed quark can combine: (T) with the spectator antiquark; (S) with the $\bar d$ emitted in the weak decay vertex of (W) with an antiquark produced by gluons somewhere else in the diagram. Our T, S and W diagrams each include all possible diagrams of the corresponding type. Similarly there are only three possible ways to produce the final $\bar D$ in $B \to \bar D V$. The $\bar c$ produced by the decay of the $\bar b$ can combine: (T) with the spectator quark; (S) with the u emitted in the weak decay vertex or (W) with a quark produced by gluons somewhere else in the diagram. These transitions can be written

$$c\bar q \to \rho^+(s\bar q)\ , \quad \bar b q \to \rho^+(\bar c q) \quad \text{for T} \tag{1a}$$

$$c\bar q \to \bar K^0(u\bar q)\ , \quad \bar b q \to \bar D^0(\bar u q) \quad \text{for S} \tag{1b}$$

$$c\bar{u} \to (s\bar{d}), \quad \bar{b}d \to (\bar{c}u) \quad \text{for W} \tag{1c}$$

where $\bar{q}$ and q denote the spectator antiquark or quark in the initial state.

Although different approaches may calculate the values of these amplitudes in different ways from different models, the results of all approaches can be described in this general form, and lead to the same general relations between the experimentally observed amplitudes and the T, S and W amplitudes.

$$A_D(\rho^+\bar{K}^0) = T + S,$$
$$A_B(\rho^+\bar{D}^0) = T_B + S_B, \tag{2a}$$
$$A_D(\rho^+K^-) = T + W,$$
$$A_B(\rho^+D^-) = T_B + W_B, \tag{2b}$$
$$A_D(V_u\bar{K}^0) = S, \quad A_B(V_d\bar{D}^0) = S_B, \tag{2c}$$
$$A_D(V_d\bar{K}^0) = W, \quad A_B(V_u\bar{D}^0) = W_B, \tag{2d}$$
$$A_D(\rho^0\bar{K}^0) = \frac{1}{\sqrt{2}} \cdot (S - W),$$
$$A_B(\rho^0\bar{D}^0) = \frac{-1}{\sqrt{2}} \cdot (S_B - W_B), \tag{2e}$$
$$A_D(\omega\bar{K}^0) = \frac{1}{\sqrt{2}} \cdot (S + W),$$
$$A_B(\omega\bar{D}^0) = \frac{1}{\sqrt{2}} \cdot (S_B + W_B), \tag{2f}$$
$$|A_D(\phi\bar{K}^0)| = \xi|W| \leqslant |W|,$$
$$|A_B(K^+\bar{D}_s)| = \xi_B|W_B| \leqslant |W_B|, \tag{2g}$$

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 ρ^0 and ω are equal mixtures of these two states with opposite relative phase. ξ and ξ_B are flavour-SU(3)-breaking parameters $\leqslant 1$ expressing the suppression of creating strange quark pairs from the vacuum.

All approaches eventually express results in terms of these three general types of transitions described in Eqs. (1) and the relations (2). One immediately notes the general feature that both T and S contribute to the exotic channels but W does not contribute since it goes via an intermediate state containing only a single $q\bar{q}$ pair. In the non-exotic channels there are W-exchange contributions and either a colour-favored or colour-suppressed diagram, but not both. 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 [16]. Thus the relations (1) and (2) cannot distinguish between W contributions due to weak W exchange and those due to strong final state rescattering of the type described in "BSW Fig. 2"; e.g. resonances.

Two different approaches have been used to explain the non-exotic enhancement present in D decays and its absence in B decays. One attributes them to strong final state interactions in channels having resonances [22,23], while others use weak interaction diagrams without taking final state interactions into account [14,18]. However, the "reverse enhancement" of exotics noted above in low-lying exclusive B decays has not previously been discussed.

The weak interaction approach suggests an enhancement in the non-exotic channels due to the W-exchange diagram, and a suppression in the exotic channels due to a "Pauli" interference between the T and S contributions claimed to be always destructive [14]. 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.

We immediately note the following inequalities from the data in Tables 1 and 2.

$$\frac{|T+S|}{|T+W|} < 1 < \frac{|T_B+S_B|}{|T_B+W_B|},$$
$$\frac{|W_B \pm S_B|}{|T_B+S_B|} \ll \frac{|W+S|}{|T+S|} \approx 1, \tag{3a}$$
$$\frac{br(\phi\bar{K}^0)}{br(\rho^0\bar{K}^0)+br(\omega\bar{K}^0)} = 0.27 \pm 0.05 \leqslant \frac{W^2}{W^2+S^2}. \tag{3b}$$

If we include a p^3 correction for phase space this becomes

$$\frac{br(\phi\bar{K}^0)}{br(\rho^0\bar{K}^0)+br(\omega\bar{K}^0)} = 0.57 \pm 0.11 \leqslant \frac{W_{\rm ps}^2}{W_{\rm ps}^2+S_{\rm ps}^2}. \tag{3c}$$

A simple qualitative explanation for the very different behaviour of the D and B amplitudes in Eq. (3a) is to assume that W^2 is appreciable for D decays as also indicated by the inequality (3b), (3c) and negligible in B decays. The $T_B \cdot S_B$ interference between amplitudes must then be constructive in contradiction with conventional wisdom.

This systematics can be reversed at higher excitations as required to obtain the same total decay rates for charged and neutral B's. A simple example is seen in the $a_1 D$ decay mode. 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.

Unfortunately the experimental statistics are not yet sufficient for conclusive tests of this scenario. 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 1.6 GeV, 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.

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 $D^+ \to \pi K_0^{*0}(1430)$, $D^0 \to \pi^+ K_0^{*-}(1430)$; in the absence of data on $K_0^{*0}\pi^0$ 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.

4.1. Application to $D \to \rho K$, $D \to \omega K$ and $D \to \phi K$ decays

We now attempt to test the above qualitative picture by quantitative analyses of the data.

We normalized the amplitudes so that

$$\frac{br(\rho^+\bar{K}^0)}{br(\nu e^+\bar{K}^0)} = 1.0 \pm 0.37 \pm 13\% = (T+S)^2 \approx [0.96; 1.0]\,, \tag{4a}$$

$$\frac{br(\rho^+K^-)}{br(\nu e^+K^-)} = 3.10 \pm 0.30 \pm 5\% = (T+W)^2 \approx [3.13; 3.07]\,, \tag{4b}$$

$$\frac{br(\rho^0\bar{K}^0)}{br(\nu e^+K^-)} = 0.35 \pm 0.05 \pm 5\% = \tfrac{1}{2}\cdot(W-S)^2 \approx [0.32; 0.36]\,, \tag{4c}$$

$$\frac{br(\omega\bar{K}^0)}{br(\nu e^+K^-)} = 0.60 \pm 0.12 \pm 5\% = \tfrac{1}{2}\cdot(W+S)^2 \approx [0.60; 0.60]\,, \tag{4d}$$

where the numbers in brackets denote the fits to the data using the parameters described below. We immediately note that

$$|A(\rho^0\bar{K}^0)| = \frac{1}{\sqrt{2}}\cdot|(S-W)| < |A(\omega\bar{K}^0)| = \frac{1}{\sqrt{2}}\cdot|(S+W)|\,, \tag{5a}$$

$$\frac{br(\rho^+K^-)}{br(\nu e^+K^-)} - \frac{br(\rho^+\bar{K}^0)}{br(\nu e^+\bar{K}^0)} = 2.10 \pm 0.48 \pm 0.20 = T\cdot(W-S) + |W|^2 - |S|^2\,, \tag{5b}$$

$$\frac{br(\rho^0\bar{K}^0)}{br(\nu e^+K^-)} + \frac{br(\omega\bar{K}^0)}{br(\nu e^+K^-)} = 0.95 \pm 0.13 \pm 5\% = |W|^2 + |S|^2\,. \tag{5c}$$

From which the inequalities (3b), (3c) gives

$$|W|^2 \geqslant 0.26 \pm 0.06 \pm 5\%\,, \quad |S|^2 \leqslant 0.69 \pm 0.08 \pm 5\%\,, \tag{5d}$$

$$|W_{ps}|^2 \geqslant 0.55 \pm 0.12 \pm 5\%\,, \quad |S_{ps}|^2 \leqslant 0.40 \pm 0.12 \pm 5\%\,. \tag{5e}$$

We now note the following qualitative features. All three amplitudes are appreciable and their interference terms are crucial for the explanations of the inequality (5a) and the difference (5b). The $S \cdot W$ and $T \cdot (W-S)$ interference terms are required to be positive.

To get a more quantitative picture we note that the four experimental equalities and the one inequality can be fit with three real amplitudes by setting

$$T = 0.83\,, \quad W = 0.95\,, \quad S = 0.15\,. \tag{6a}$$

Generalising to complex amplitudes they can also be fit by setting

$$T = 1.08 \cdot e^{-i(\pi/3)}\,, \quad W = 0.94\,,$$
$$S = 0.26 \cdot e^{i(\pi/3)}\,. \tag{6b}$$

The values obtained by substituting these parameters are indicated in brackets in Eqs. (4). These solutions are not unique but are primarily to illustrate that present data allow alternative descriptions that are open to experimental discrimination. The second fit shows that with complex phases it is possible for $T \cdot W$ and $T \cdot S$ terms to have opposite signs even though both $S \cdot W$ and $T \cdot S$ are positive, thereby allowing the negative $T \cdot S$ term as suggested by the Pauli effect. Although there is little point in further detailed analysis with present data, the fact that there are two solutions with opposite signs for the $T \cdot S$ interference is sufficiently interesting to guide further experimental investigation. This is of particular interest in view of the apparent relation with the unexpected evidence in B decays where the $T \cdot S$ term is definitely positive.

In both solutions the magnitudes of the T and W amplitudes are seen to be roughly equal and the S amplitude is much smaller. These features are in accord with the picture of resonance enhancement in the non-exotic channels. In this picture the W amplitude has a contribution from the final-state rescattering as noted in "BSW Fig. 2". The basic physics in this qualitative argument lies in relative phases determined by the isospinology, the experimental result and the inequality (3b), (3c).

Note that the $\rho - \omega$ mixing of $u\bar{u}$ and $d\bar{d}$ states and the large ϕK mode forbidden by the S and T amplitudes play crucial roles in this analysis. Both the relative phase of the W and S amplitudes and the fact that the W amplitude cannot be small are determined by the experimental inequalities (5a).

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 and model dependent calculation involving point-like and hadronic form factors for the ρ 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, even if the solution with the positive phase is valid for the low-lying exclusive states.

4.2. Application to $B \to XD$ decays

In the $B \to XD$ 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

$$\Gamma^{+0} \equiv |A_B(X^+\bar{D}^0)|^2 = |T_B + S_B|^2$$
$$\approx T_B^2 + 2T_B \cdot S_B\,, \tag{7a}$$
$$\Gamma^{+-} \equiv |A_B(X^+D^-)|^2 = |T_B + W_B|^2$$
$$\approx T_B^2 + 2T_B \cdot W_B\,, \tag{7b}$$
$$\Gamma^{00} \equiv |A_B(X^0\bar{D}^0)|^2 = \tfrac{1}{2} \cdot |(S_B - W_B)|^2\,. \tag{7c}$$

Then to lowest order in the small amplitudes,

$$\frac{1}{4} \cdot \frac{|\Gamma^{+0} - \Gamma^{+-}|^2}{\Gamma^{+0} + \Gamma^{+-}} \approx \frac{|T_B \cdot (S_B - W_B)|^2}{2T_B^2}$$
$$= \Gamma^{00} \cos^2\theta\,, \tag{8a}$$

where

$$\cos\theta = \frac{T_B \cdot (S_B - W_B)}{|T_B||S_B - W_B|}\,. \tag{8b}$$

The present data show only upper bounds for Γ^{00} which satisfy these relations for all the XD states listed above in Table 2.

However, these data already reveal the interesting and surprising systematics that *for B decays the exotic branching ratios are consistently larger than the non-exotic* and that this difference comes from an interference term between the T and $W - S$ combination of amplitudes. The direct terms proportional to squares of these small amplitudes are seen from the data to be below the presently measured upper limits. In principle the relation (8) does not specify which of the two small amplitudes dominates in the interference term. However, we note that it is possible to give a unified description of both D and B decays by having a small colour-suppressed amplitude interfering *constructively* with the colour-favored amplitude.

Thus we see that in contrast to the D decays where

$$W_D \geqslant T_D > S_D \tag{9a}$$

the B system shows

$$T_B > S_B \gg W_B \,. \tag{9b}$$

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, since it can also be suppressed by factors in weak diagrams.

5. Comparison of B and D decays

For a ball-park estimate set $T = 1$, $W = 1$ and $S = 1/3$ 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:

$$\Gamma_D^{+0}/\Gamma_D^{+-}/\Gamma_D^{00} = 4:9:\tfrac{1}{2} \tag{10a}$$

for D decays and

$$\Gamma_B^{+0}/\Gamma_B^{+-}/\Gamma_B^{00} = 16:9:\tfrac{1}{2} \tag{10b}$$

for B decays. We also obtain the non-trivial qualitative prediction

$$\frac{br(B^0 \to K^+\bar{D}_s)}{br(B^0 \to \rho^0\bar{D}^0) + br(B^0 \to \omega\bar{D}^0)} \ll \frac{br(D^0 \to \phi\bar{K}^0)}{br(D^0 \to \rho^0\bar{K}^0) + br(D^0 \to \omega\bar{K}^0)} = 0.27 \pm 0.05\,. \tag{10c}$$

Present B-decay data are inadequate to test this prediction, since there are only upper limits on all modes. It will be interesting to check this comparison of the relative importance of the W and S amplitudes in future data.

The ratios (10a) and (10b) follow from a clearly oversimplified analysis, 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.

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

$$br(D^+ \to \pi^+\bar{K}^{0*}) \sim (T+S)^2 = 2.2 \pm 0.4\%\,.$$

from which if we ignore modifications arising from phase space and exclusive form factors (which tend to counterbalance [24]), we may expect

$$br(D^+ \to \pi^+\rho^0) \sim \frac{(T+S)^2}{2} \times \sin^2\theta \sim 0.05\%$$

(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 $\pi^+\bar{K}^{0*}$ also is "small" due to destructive interference (which is consistent with the analysis of Section 2.1 applied to Eqs. (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 [1] 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 [25–27]. 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 $O(200$ 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 [22].

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 ~ 5 GeV. Unlike the K and π system where the lightest hybrids or prominent radial excitations are expected around 2 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 ~ 3.5 GeV region, far below the 5 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 πK and within errors for πK^*; it may also be true (possibly) for ρK^* (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 [21]). It does not arise for the $a_1 K$ and ρK 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 (2) satisfy the sum rule

$$A(\rho^+\bar{K}^0) = A(\rho^+K^-) + \sqrt{2}\cdot A(\rho^0\bar{K}^0)\,. \qquad (11)$$

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. Relative phases of these amplitudes are unobservable and determined by conventions which give physically equivalent triangular inequalities for the experimental branching ratio data. It is interesting that for this case the data are

$$\frac{\sqrt{\{br(\rho^+K^-)\}}}{\sqrt{\{br(\nu e^+K^-)\}}} = 1.66 \pm 0.11 \pm 3\%\,,$$

$$\sqrt{2}\cdot\frac{\sqrt{\{br(\rho^0\bar{K}^0)\}}}{\sqrt{\{br(\nu e^+K^-)\}}} = 0.76 \pm 0.07 \pm 3\%\,, \qquad (12a)$$

$$\frac{\sqrt{\{br(\rho^+\bar{K}^0)\}}}{\sqrt{\{br(\nu e^+\bar{K}^0)\}}} = 1.0 \pm 0.18 \pm 6.5\%\,. \qquad (12b)$$

Then

$$\frac{\sqrt{\{br(\rho^+K^-)\}}}{\sqrt{\{br(\nu e^+K^-)\}}} - \sqrt{2}\cdot\frac{\sqrt{\{br(\rho^0\bar{K}^0)\}}}{\sqrt{\{br(\nu e^+K^-)\}}} = 0.90 \pm 0.21 \pm 7\%\,, \qquad (12c)$$

which is within experimental errors of the lower limit of the inequality.

A similar approach can be made for $\rho\bar{K}^*(892)$, $\pi\bar{K}$ and $\pi\bar{K}^*$ 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 ρ sum rules show similar behavior and the behavior of pionic and ρ sum rules are very difficult 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 ρ 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

$$A(\rho^+\bar{D}^0) - A(\rho^+D^-) = -\sqrt{2}\cdot A(\rho^0\bar{D}^0)\,. \tag{13}$$

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 (13).

The relevant data are

$$\frac{\sqrt{\{br(\rho^+D^-)\}}}{\sqrt{\{br(\nu e^+D^-)\}}} = 0.64 \pm 0.05 \pm 13\%\,,$$

$$\sqrt{2}\cdot\frac{\sqrt{\{br(\rho^0\bar{D}^0)\}}}{\sqrt{\{br(\nu e^+D^-)\}}} < 0.28\,, \tag{14a}$$

$$\frac{\sqrt{\{br(\rho^+\bar{D}^0)\}}}{\sqrt{\{br(\nu e^+\bar{D}^0)\}}} = 0.91 \pm 0.06 \pm 22\%\,. \tag{14b}$$

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 θ in Eq. (8).

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 $\pi K(^*)$ the data were suggestive that the neutral decays were dominated by $I = 1/2$. This is not the case for $B^0 \to \pi D$ though this is not ruled out for the $B^0 \to \pi D^*$.

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 $\bar{B}B$ 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 ψK_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 3π final state, all neutral three-pion states could be used in CP-violation experiments by analogy with ψK_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 3π 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 3π 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 [28] 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 non-exotic 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.

Acknowledgements

We are grateful to J. Appel, C. Damerell, Y. Grossman, M. Sokoloff and S. Stone for discussions.

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