Large final-state phases in heavy meson decays

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(Received 6 April 1999; published 13 September 1999)

An attempt is made to identify circumstances under which the weak decays of D and B mesons may display large differences between eigenphases of strong final-state interactions. There are several cases in which rescattering from other final states appears to enhance decay rates with respect to estimates based on the factorization hypothesis. [S0556-2821(99)04519-1]

PACS number(s): 13.25.−k, 11.30.Hv, 12.40.Nn, 13.75.Lb

I. INTRODUCTION

Ever since the discovery of CP violation in neutral kaon decays [1], attempts have been made to learn more about its origin. The ratios $R_{+-}=\Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_S\to\pi^+\pi^-)$ and $R_{00}=\Gamma(K_L\to\pi^0\pi^0)/\Gamma(K_S\to\pi^0\pi^0)$ are predicted to be equal in any model (such as a superweak [2] one) in which CP violation arises purely via K^0-$\bar{K}^0$ mixing, but can differ from one another by up to $O(1\%)$ [3] in the Kobayashi-Maskawa (KM) theory [4] based on phases in weak coupling constants.

The two most recent previous measurements of $\Delta R \equiv (R_{+-}/R_{00})-1$:$(0.44\pm0.35)\%$ (Fermilab E731 [5]) and $(1.38\pm0.39)\%$ (CERN NA31 [6]) have now been joined by those of a new experiment with more compelling statistics, which finds $\Delta R=(1.68\pm0.25)\%$ (Fermilab E832 [7]). Superweak models are ruled out. The effect is near the upper limit of theoretical estimates [3], but can be accommodated by reasonable values of hadronic matrix elements and strange quark mass. The new result will reduce the uncertainty on the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [4,8] describing the weak charge-changing couplings of quarks.

A key test of the KM theory involves decays of B mesons (containing b quarks). CP violation can manifest itself as follows in such decays:

(1) Decays of neutral B mesons to CP eigenstates such as $J/\psi K_S$ and $\pi\pi$ can directly probe CKM phases, since their interpretation is generally immune to questions of strong final-state interactions. However, such studies require identification of the flavor ($B^0=\bar{b}d$ or $\bar{B}^0=b\bar{d}$) of the neutral B meson at the time of production. This requirement can be quite demanding. It has been addressed in a recent experiment by the CDF Collaboration [9] at the Fermilab proton-antiproton collider, which finds a difference between the rates for $B^0\to J/\psi K_S$ and $\bar{B}^0\to J/\psi K_S$ at slightly under the 2σ level. Forthcoming electron-positron and hadron studies should prove much more incisive.

(2) Decays of B mesons to "self-tagging" final states f, in which one can distinguish f (e.g., $K^+\pi^-$) from its CP-conjugate $\bar{f}$ (e.g., $K^-\pi^+$), can manifest a CP-violating asymmetry if there are two decay channels characterized by differing weak phases $\phi_{1,2}$ and strong phases $\delta_{1,2}$. Writing the decay amplitudes as

$$\mathcal{A}(B\to f)=a_1 e^{i\phi_1}e^{i\delta_1}+a_2 e^{i\phi_2}e^{i\delta_2}, \tag{1}$$

$$\mathcal{A}(\bar{B}\to\bar{f})=a_1 e^{-i\phi_1}e^{i\delta_1}+a_2 e^{-i\phi_2}e^{i\delta_2}, \tag{2}$$

we note that the weak phases ϕ_i change sign under CP conjugation, whereas the strong phases δ_i do not. The decay rate asymmetry $A(f)$ is then given by

$$A(f)\equiv\frac{\Gamma(B\to f)-\Gamma(\bar{B}\to\bar{f})}{\Gamma(B\to f)+\Gamma(\bar{B}\to\bar{f})}$$
$$=\frac{2a_1 a_2 \sin(\phi_1-\phi_2)\sin(\delta_1-\delta_2)}{a_1^2+a_2^2+2a_1 a_2 \cos(\phi_1-\phi_2)\cos(\delta_1-\delta_2)}. \tag{3}$$

A nonzero asymmetry of this type requires both the weak phases and the strong phases to differ from one another in at least two channels. Whereas it is straightforward to estimate weak phase differences in typical theories such as that of Kobayashi and Maskawa, the anticipation of strong phase differences is much more problematic [10,11].

In the present paper we examine several instances of large strong phase differences, in search of a common thread whereby other such cases can be identified. We build upon several studies by Suzuki which have identified large final-state phases in J/ψ [12,13] (Sec. II) and charmed meson [14] (Sec. III) decays. We conclude that large final-state phases are a possibility in any process in which a pair of quarks annihilates hadronically. Such cases include not only those studied by Suzuki in J/ψ decays, but penguin amplitudes contributing to $b\to s$ processes (Sec. IV), including those involving η' production. The case of B decays to charmed final states, in which large final-state phases do not appear to be encountered [14,15], is treated in Sec. V.

Although cases with large final-state phases cannot be identified with certainty, the measurement of $A(f)$ and knowledge of a_1 and a_2 in Eq. (3) permit one to place a lower bound on $|\sin(\phi_1-\phi_2)|$, which can be quite useful in constraining CKM parameters. It is thus useful to identify promising cases in which the asymmetry $A(f)$ can be large. We summarize these cases, noting open experimental questions, in Sec. VI.

II. CHARMONIUM DECAYS

A. J/ψ decays

Recently Suzuki has noted that the three-gluon and single-photon amplitudes in decays of the form $J/\psi \to VP$ [12] and $J/\psi \to PP$ [13] appear to have relative phases of approximately $\pi/2$. Here and subsequently, V will denote a light vector meson: $V = (\rho, \omega, K^*, \phi)$, while P will denote a light pseudoscalar meson: $P = (\pi, K, \eta, \eta')$. Without retracing Suzuki's whole analysis, we review the essential points, beginning with the three VP decays $J/\psi \to K^{*+}K^-$, $J/\psi \to K^{*0}\bar{K}^0$, and $J/\psi \to \omega\pi^0$. We shall show that the amplitudes for these three processes form a triangle with significant area, from which one can infer nontrivial relative phases of strong and electromagnetic contributions.

We consider only three-gluon and one-photon contributions, neglecting others involving (for example) two gluons and one photon and neglecting contributions from isospin mixing in the neutral pion. The strong-decay amplitudes for $J/\psi \to K^{*+}K^-$ and $J/\psi \to K^{*0}\bar{K}^0$ are equal, while the decay $J/\psi \to \omega\pi^0$ is isospin-violating and proceeds only electromagnetically. The one-photon amplitudes for production of $K^{*+}K^-$, $K^{*0}\bar{K}^0$, and $\omega\pi^0$ are proportional, respectively, to $\mu_u + \mu_s$, $\mu_d + \mu_s$, and $\mu_u - \mu_d$, where $\mu_i = Q_i|e|/(2m_i)$ is the magnetic moment of quark i whose charge and mass are Q_i and m_i.

The three amplitudes of interest can then be written in terms of two parameters A and B and a quark mass ratio $r = m_{u,d}/m_s$ as

$$\mathcal{A}(J/\psi \to K^{*+}K^-) = A + B\left(\frac{2}{3} - \frac{r}{3}\right), \quad (4)$$

$$\mathcal{A}(J/\psi \to K^{*0}\bar{K}^0) = A + B\left(-\frac{1}{3} - \frac{r}{3}\right), \quad (5)$$

$$\mathcal{A}(J/\psi \to \omega\pi^0) = B, \quad (6)$$

so that they satisfy a triangle relation

$$\mathcal{A}(J/\psi \to K^{*+}K^-) - \mathcal{A}(J/\psi \to K^{*0}\bar{K}^0) = \mathcal{A}(J/\psi \to \omega\pi^0). \quad (7)$$

To estimate the relative amplitudes, we use the observed branching ratios [16]:

$$\mathcal{B}(J/\psi \to K^{*+}K^-) = (0.25 \pm 0.02)\%,$$

$$\mathcal{B}(J/\psi \to K^{*0}\bar{K}^0) = (0.21 \pm 0.02)\%,$$

$$\mathcal{B}(J/\psi \to \omega\pi^0) = (0.042 \pm 0.006)\%. \quad (8)$$

We define magnitudes of amplitudes to be the square roots of these branching ratios. Kinematic SU(3)-breaking may be included by correcting the $\omega\pi^0$ amplitude for the slightly larger center-of-mass 3-momentum in $J/\psi \to \omega\pi^0$ ($p_{\omega\pi} = 1446$ MeV/c as compared with $p_{K^*\bar{K}} = 1373$ MeV/c in $J/\psi \to K^{*+}K^-$ and 1371 MeV/c in $J/\psi \to K^{*0}\bar{K}^0$). For a P-wave decay, the correction factor $\rho^{1/2} = (p_{K^*\bar{K}}/p_{\omega\pi})^{3/2}$
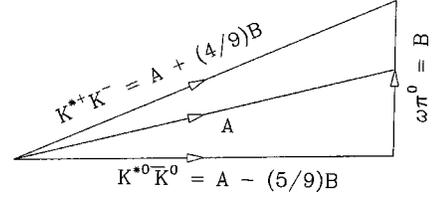
FIG. 1. Triangle of amplitudes in $J/\psi \to VP$ decays. Here A and B are strong and electromagnetic amplitudes, respectively.

$= 0.925$ should thus multiply the square root of the $\omega\pi^0$ branching ratio in extracting the amplitude satisfying Eq. (7). We then find

$$|\mathcal{A}(J/\psi \to K^{*+}K^-)| = 0.050 \pm 0.002,$$

$$|\mathcal{A}(J/\psi \to K^{*0}\bar{K}^0)| = 0.046 \pm 0.002,$$

$$|\mathcal{A}(J/\psi \to \omega\pi^0)| = |B| = 0.0190 \pm 0.0014. \quad (9)$$

These form a triangle which is roughly isosceles in shape as a result of the near equality of the $K^*\bar{K}$ amplitudes. The base (the $\omega\pi^0$ side) corresponds to the electromagnetic amplitude B, while the sides are dominated by the strong contribution A.

In order to specify the relative phase of strong and electromagnetic contributions, one needs the ratio r. We take $r \simeq 2/3$ (the corresponding ratio for constituent-quark masses, which fits electromagnetic transitions of the form $V \to P_\gamma$ [17]). The electromagnetic contributions to $\mathcal{A}(J/\psi \to K^{*+}K^-)$ and $\mathcal{A}(J/\psi \to K^{*0}\bar{K}^0)$ are then $(4/9)B$ and $-(5/9)B$, respectively, so that the triangle has the shape illustrated in Fig. 1. The magnitude of the strong amplitude is $|A| \simeq 0.047$.

A brief calculation of the relative phase δ of A and B yields the relation

$$\cos\delta = \frac{\mathcal{B}(K^{*+}K^-) - \mathcal{B}(K^{*0}\bar{K}^0) + \rho\mathcal{B}(\omega\pi^0)/9}{2|A||B|}$$

$$= 0.25 \pm 0.16, \quad (10)$$

or $\delta = (76^{+9}_{-10})°$. The relative phase between the strong and electromagnetic amplitudes is large and consistent with 90°. We have not made use of the $J/\psi \to \rho\pi$ amplitude since its strong contribution (which predominates over a very small electromagnetic one) is related to A only through flavor SU(3), which we do not employ. For similar reasons, we do not consider other final states such as $\omega\eta$ and $\omega\eta'$. When these decays are included in the fit, the results do not change much; Suzuki [12] obtains $\delta = 80°$.

A similar analysis yields a large relative phase between strong and electromagnetic contributions to $J/\psi \to PP$ decays. We consider the processes $J/\psi \to K^+K^-$ and $J/\psi \to K^0\bar{K}^0$ [whose strong amplitudes vanish in the limit of flavor SU(3)] and $J/\psi \to \pi^+\pi^-$ [whose strong amplitude vanishes in the limit of isospin conservation]. The corresponding amplitudes may be expressed as

$K^+ K^- = A' + B'$

$\pi^+ \pi^- = B'$
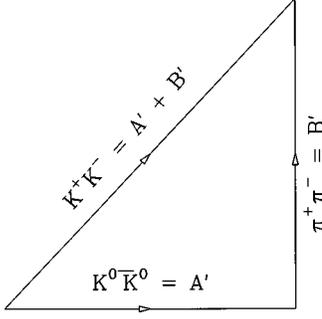
$K^0 \bar{K}^0 = A'$

FIG. 2. Triangle of amplitudes in $J/\psi \to PP$ decays. Here A' and B' are strong and electromagnetic amplitudes, respectively.

$$\mathcal{A}(J/\psi \to K^+ K^-) = A' + B'(Q_u - Q_s),$$

$$\mathcal{A}(J/\psi \to K^0 \bar{K}^0) = A' + B'(Q_d - Q_s),$$

$$\mathcal{A}(J/\psi \to \pi^+ \pi^-) = A' + B'(Q_u - Q_d), \qquad (11)$$

satisfying the triangle relation

$$\mathcal{A}(J/\psi \to K^+ K^-) - \mathcal{A}(J/\psi \to K^0 \bar{K}^0) = \mathcal{A}(J/\psi \to \pi^+ \pi^-). \qquad (12)$$

This relation is violated slightly by some of the SU(3)-breaking terms considered by Suzuki [13], but is sufficient for our purposes. As in the previous calculation, we correct the $\pi^+ \pi^-$ amplitude for the center-of-mass 3-momentum in $J/\psi \to \pi^+ \pi^-$ ($p_\pi = 1542$ MeV/c as compared with $p_K = 1468$ MeV/c in $J/\psi \to K^+ K^-$ and 1466 MeV/c in $J/\psi \to K^0 \bar{K}^0$). The P-wave correction factor to the square root of the $\pi^+ \pi^-$ branching ratio, needed to extract the amplitude satisfying Eq. (12), is then $\rho^{1/2} = (p_K/p_\pi)^{3/2} = 0.929$.

We use the branching ratios [16]

$$\mathcal{B}(J/\psi \to K^+ K^-) = (2.37 \pm 0.31) \times 10^{-4},$$

$$\mathcal{B}(J/\psi \to K^0 \bar{K}^0) = (1.08 \pm 0.14) \times 10^{-4},$$

$$\mathcal{B}(J/\psi \to \pi^+ \pi^-) = (1.47 \pm 0.23) \times 10^{-4}. \qquad (13)$$

The amplitudes which are the square roots of these branching ratios, correcting the $\pi^+ \pi^-$ amplitude for the kinematic factor mentioned above, are

$$|\mathcal{A}(J/\psi \to K^+ K^-)| = |A' + B'| = (1.54 \pm 0.10) \times 10^{-2},$$

$$|\mathcal{A}(J/\psi \to K^0 \bar{K}^0)| = |A'| = (1.04 \pm 0.07) \times 10^{-2},$$

$$|\mathcal{A}(J/\psi \to \pi^+ \pi^-)| = |B'| = (1.12 \pm 0.08) \times 10^{-2}. \quad (14)$$

These form an isosceles right triangle, as illustrated in Fig. 2.

The relative phase δ' of A' and B' is given by

$$\cos \delta' = \frac{\mathcal{B}(K^+ K^-) - \mathcal{B}(K^0 \bar{K}^0) - \rho \mathcal{B}(\pi^+ \pi^-)}{2|A'||B'|} = 0.01 \pm 0.19, \qquad (15)$$

TABLE I. Branching ratios of the ψ' to specific hadronic final states.

Final state	B.r. or 90% c.l. upper limit ($\times 10^{-5}$)
$\rho\pi$	<2.8
$\omega\pi^0$	$3.8 \pm 1.7 \pm 1.1$
$K^{*+} K^- + $c.c.	<3.0
$K^{*0} \bar{K}^0 + $c.c.	$8.1 \pm 2.4 \pm 1.6$

or $\delta' = (89 \pm 10)°$. This is again in accord with Suzuki's result [13].

B. ψ' decays

The suppression of certain decay modes of the ψ' such as $\rho\pi$ and $K^* \bar{K} + $c.c. [18] has puzzled physicists for nearly 20 years [19]. The BES Collaboration [20] has now reported the isospin-violating decay $\psi' \to \omega\pi^0$ at a level above the upper limit for the isospin-allowed decay $\psi' \to \rho\pi$, and has seen the decay $\psi' \to K^{*0}\bar{K}^0$ at a level considerably above the upper limit for the isospin-related decay $\psi' \to K^{*+} K^-$. These results are summarized in Table I, whose data are taken from Ref. [20].

An analysis similar to that performed for $J/\psi \to VP$ yields the amplitudes (expressed again as square roots of branching ratios, with a kinematic correction for $\omega\pi^0$).

$$|\mathcal{A}(\psi' \to K^{*+} K^-)| < 3.9 \times 10^{-3},$$

$$|\mathcal{A}(\psi' \to K^{*0} \bar{K}^0)| = (6.4 \pm 2.3) \times 10^{-3},$$

$$|\mathcal{A}(\psi' \to \omega\pi^0)| = (5.8 \pm 1.6) \times 10^{-3}. \qquad (16)$$

These should satisfy the sum rule (7) with ψ' replacing J/ψ.

The data are not yet precise enough to specify the shape of the corresponding $\psi' \to VP$ amplitude triangle. The $\omega\pi^0$ decay requires an electromagnetic contribution to be present. If this were the only amplitude contributing to all three processes, one would expect $\mathcal{A}(K^{*+} K^-) = (4/5)\mathcal{A}(K^{*0}\bar{K}^0) = (4/9)\mathcal{A}(\omega\pi^0)$, which is just at the limit of error bars for each amplitude, but not yet firmly ruled out. [Take, for example, $\mathcal{A}(\omega\pi^0) = 7.4 \times 10^{-3}$, $\mathcal{A}(K^{*0}\bar{K}^0) = 4.1 \times 10^{-3}$, and $\mathcal{A}(K^{*+} K^-) = 3.3 \times 10^{-3}$.] Thus, since the presence of the strong amplitude has not yet been demonstrated, its phase with respect to the electromagnetic one is still an open question.

III. CHARMED MESON DECAYS

A. Isospin decomposition

The decays of the nonstrange charmed mesons $D^+ = c\bar{d}$ and $D^0 = c\bar{u}$ to final states consisting of one strange meson ($\bar{K}$ or $\bar{K}^*$) and one $I = 1$ nonstrange meson (π or ρ) are governed by the $\Delta I = \Delta I_3 = 1$ subprocess $c \to su\bar{d}$ and thus

are characterized by two amplitudes $A_{1/2}$ and $A_{3/2}$ labeled by the total isospin of the final state. For example, the amplitudes for the decays $D \to \bar{K}\pi$ are given by

$$\mathcal{A}(D^+ \to \bar{K}^0 \pi^+) = A_{3/2},$$

$$\mathcal{A}(D^0 \to K^- \pi^+) = \frac{2}{3} A_{1/2} + \frac{1}{3} A_{3/2},$$

$$\mathcal{A}(D^0 \to \bar{K}^0 \pi^0) = -\frac{\sqrt{2}}{3} A_{1/2} + \frac{\sqrt{2}}{3} A_{3/2}, \qquad (17)$$

and thus satisfy a triangle relation

$$\mathcal{A}(\bar{K}^0 \pi^+) = \mathcal{A}(K^- \pi^+) + \sqrt{2} \mathcal{A}(\bar{K}^0 \pi^0), \qquad (18)$$

where we have omitted the initial particle. By studying decay rates alone, one can determine the shape of this triangle and thus learn the relative phases of isospin amplitudes. We shall continue the discussion with the $D \to \bar{K}\pi$ example; it also holds for $D \to \bar{K}^* \pi$ and $D \to \bar{K}\rho$. We do not use information obtained in some analyses [30,31,32,33] from relative phases of bands in the Dalitz plots, but will return to this question in the subsequent discussion.

The magnitude of the $I = 3/2$ amplitude is obtained from the $D^+ \to \bar{K}^0 \pi^+$ partial width. Omitting all kinematic factors, we have $|A_{3/2}|^2 = \Gamma(\bar{K}^0 \pi^+)$. The magnitude of the $I = 1/2$ amplitude is obtained from the combination

$$|A_{1/2}|^2 = \frac{3}{2} [\Gamma(K^- \pi^+) + \Gamma(\bar{K}^0 \pi^0)] - \frac{1}{2} \Gamma(\bar{K}^0 \pi^+). \qquad (19)$$

The relative phase δ_I between isospin amplitudes is given by

$$\cos \delta_I = \frac{3\Gamma(K^- \pi^+) + \Gamma(\bar{K}^0 \pi^+) - 6\Gamma(\bar{K}^0 \pi^0)}{4|A_{1/2} A_{3/2}|}. \qquad (20)$$

B. Graphical decomposition

As stressed by Suzuki [14], for decays of D and B mesons in which multiparticle final states can play a large role, two-body isospin amplitudes may not be the most significant quantities. The relation (18) also is implied by the decomposition of the decay amplitudes in terms of color-favored tree (T), color-suppressed (C), and exchange (E) amplitudes [21,22]:

$$\mathcal{A}(\bar{K}^0 \pi^+) = T + C, \quad \mathcal{A}(K^- \pi^+) = T + E,$$

$$\mathcal{A}(\bar{K}^0 \pi^0) = (C - E)/\sqrt{2}. \qquad (21)$$

The set T, C, and E is overcomplete. In principle, one can assume that T and C have zero phase relative to one another, and that all the final-state interaction effects are concentrated in E. One still needs information on the relative magnitudes of T and C, which one may either take from quantum chro-

TABLE II. Charmed meson lifetimes, in fs.

State	PDG	CLEO	Average
D^+	1057 ± 15	$1033.6 \pm 22.1^{+9.9}_{-12.7}$	1051 ± 13
D^0	415 ± 4	$408.5 \pm 4.1^{+3.5}_{-3.4}$	412.7 ± 3.2

modynamics (QCD) [23,24], or by applying the factorization hypothesis and the relation between nonleptonic and semileptonic processes [25,26],

$$\frac{\Gamma(D^0 \to K^- \pi^+)_T}{d\Gamma(D^0 \to K^- l^+ \nu_l)/dq^2|_{q^2 = m_\pi^2}} = 6\pi^2 f_\pi^2 |V_{ud}|^2 = 0.98 \text{ GeV}^2,$$
$$(22)$$

to data on the spectrum in semileptonic decays (see, e.g., [27]). The use of a phenomenological E amplitude to parametrize final-state interactions would be an alternative to the more conventional short-distance descriptions of such effects in charmed-particle decays, which can account for some but perhaps not all of the differences among charmed-particle lifetimes [28]. We leave this possibility for a future investigation.

C. Results of isospin analysis

To compare amplitudes for D^0 and D^+ decays, we calculate decay rates using branching ratios and lifetimes. The Particle Data Group values [16] are averaged with new CLEO values [29] in Table II; we use the new averages in what follows. We summarize the relevant branching ratios and decay rates in Table III.

The values of isospin amplitudes (defined as square roots of rates, without any correction for kinematic factors) and corresponding phases are shown in Table IV. In accord with many previous results [30,31,32,33], the relative phases of the $I = 1/2$ and $I = 3/2$ amplitudes are consistent with 90° for the $\bar{K}\pi$ and $\bar{K}^* \pi$ channels and with 0° for the $\bar{K}\rho$ channel. The value of $\delta_I(\bar{K}\pi)$ agrees with that of Suzuki [14]. The

TABLE III. D^+ and D^0 branching ratios and decay rates.

Mode	Branching ratio (%)	Decay rate ($\times 10^{10}$ s^{-1})
	D^+ decays	
$\bar{K}^0 \pi^+$	2.89 ± 0.26	2.75 ± 0.25
$\bar{K}^{*0} \pi^+$	1.90 ± 0.19	1.81 ± 0.18
$\bar{K}^0 \rho^+$	6.6 ± 2.5	6.3 ± 2.4
	$D^0 \to (-+)$ decays	
$K^- \pi^+$	3.85 ± 0.09	9.33 ± 0.23
$K^{*-} \pi^+$	5.1 ± 0.4	12.4 ± 1.0
$K^- \rho^+$	10.8 ± 1.0	26.2 ± 2.4
	$D^0 \to (00)$ decays	
$\bar{K}^0 \pi^0$	2.12 ± 0.21	5.14 ± 0.51
$\bar{K}^{*0} \pi^0$	3.2 ± 0.4	7.8 ± 1.0
$\bar{K}^0 \rho^0$	1.21 ± 0.17	2.93 ± 0.41

TABLE IV. Isospin amplitudes and relative phases δ_I for D decays.

Mode	$|A_{1/2}|$	$|A_{3/2}|$	δ_I
	($\times 10^5$ s$^{-1/2}$)		(degrees)
$\bar{K}\pi$	4.51 ± 0.23	1.66 ± 0.08	90 ± 7
$\bar{K}^*\pi$	5.43 ± 0.19	1.35 ± 0.07	105 ± 14
$\bar{K}\rho$	6.36 ± 0.30	2.51 ± 0.47	<27 (1σ)

FIG. 3. Triangle of amplitudes in $D \to \bar{K}\pi$ decays. Subscripts on amplitudes denote total isospin.

relationship of the amplitudes to one another is illustrated in Fig. 3, showing the relative phase near 90°.

The amplitude triangle for $D \to \bar{K}^*\pi$ (Fig. 4) is qualitatively similar to that in Fig. 3, but the (00) and $(-+)$ sides are longer in proportion to the $(0+)$ side, so $|A_{1/2}/A_{3/2}|$ is larger. The amplitude relation for $D \to \bar{K}\rho$ degenerates into a straight line, since the central value of $\cos \delta_I$ exceeds 1. Put differently, the square roots of the $\bar{K}\rho$ rates in Table III satisfy $(K^-\rho^+)^{1/2} > (\bar{K}^0\rho^+)^{1/2} + (2\bar{K}^0\rho^0)^{1/2}$.

Resonances in $I = 1/2$ channels (they have never been seen in $I = 3/2$ channels) can contribute to the $D \to \bar{K}\pi$ and $\bar{K}^*\pi$ processes [34,35,36]. One needs two different states, since the $\bar{K}\pi$ state with total angular momentum $J=0$ has even parity while the $J=0$ $\bar{K}^*\pi$ state has odd parity. Candidates for the even-parity [37] and odd-parity [38] state exist. The odd-parity resonance should couple much more strongly to $\bar{K}^*\pi$ than to $\bar{K}\rho$ in order to explain the absence of a large final-state phase in the $\bar{K}\rho$ channel. However, it has only been reported in the $\bar{K}\phi$ channel [38].

D. Interference between bands on Dalitz plot

In Dalitz plot analyses of $D \to \bar{K}^*\pi$ and $D \to \bar{K}\rho$, several cross-checks of relative phases of amplitudes can be performed [30,31,32,33]. We enumerate each three-body final state and the information it provides.

(1) $D^0 \to K^-\pi^+\pi^0$ contributes to $K^-\rho^+$, $K^{*-}\pi^+$, and $\bar{K}^{*0}\pi^0$. The amplitude triangle construction for $D \to \bar{K}^*\pi$ implies a relative phase between the $K^{*-}\pi^+$ and $\bar{K}^{*0}\pi^0$ amplitudes (cf. Fig. 4) of

$$\delta_{K^{*-}\pi^+,\bar{K}^{*0}\pi^0}$$

$$= \cos^{-1} \frac{\Gamma(\bar{K}^{*0}\pi^+) - 2\Gamma(\bar{K}^{*0}\pi^0) - \Gamma(K^{*-}\pi^+)}{2\sqrt{2}|\mathcal{A}(\bar{K}^{*0}\pi^0)\mathcal{A}(K^{*-}\pi^+)|}$$

$$= (160^{+20}_{-14})^\circ. \tag{23}$$

The E687 Collaboration [33], for comparison, obtains $\delta_{K^{*-}\pi^+,K^-\rho^+} = (162 \pm 10 \pm 7 \pm 4)^\circ$ and $\delta_{\bar{K}^{*0}\pi^0,K^-\rho^+} = (-2 \pm 12 \pm 23 \pm 2)^\circ$, while the Mark III Collaboration [30] finds $\delta_{K^{*-}\pi^+,K^-\rho^+} = (154 \pm 11)^\circ$ and $\delta_{\bar{K}^{*0}\pi^0,K^-\rho^+} = (7 \pm 7)^\circ$. In both cases the $K^-\rho^+$ amplitude was taken to be real in the analysis of the $K^-\pi^+\pi^0$ final state. The first two E687 errors are statistical and systematic, respectively. The last
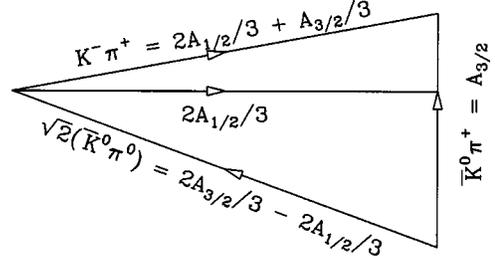
E687 error is associated with the uncertainty in the relative contributions of specific final states to the Dalitz plot. The agreement with Eq. (23) is satisfactory.

The E691 Collaboration chooses a reference phase of 0° for the nonresonant amplitude. With respect to this phase, they find $\delta_{K^{*-}\pi^+} = (-112 \pm 9)^\circ$, $\delta_{\bar{K}^{*0}\pi^0} = (167 \pm 9)^\circ$, $\delta_{K^-\rho^+} = (40 \pm 7)^\circ$. It is less clear whether this result agrees so well with Eq. (23).

(2) $D^0 \to \bar{K}^0\pi^+\pi^-$ contributes to $K^{*-}\pi^+$ and $\bar{K}^0\rho^0$. Our previous discussion implies that $\bar{K}^0\rho^0$ and $K^-\rho^+$ should be relatively real, so we expect $\delta_{K^{*-}\pi^+,\bar{K}^0\rho^0} = \delta_{K^{*-}\pi^+,K^-\rho^+}$. Reference [33] obtains $(136 \pm 6 \pm 2 \pm 2)^\circ$, while Ref. [32] obtains $(137 \pm 7)^\circ$ for the left-hand side, in adequate but not perfect agreement with the values quoted above for the right-hand side. Reference [30] obtains $\delta_{\bar{K}^0\rho^0} = (93 \pm 30)^\circ$ in a convention in which $\delta_{K^{*-}\pi^+} = 0$. This is not particularly close to Eq. (23). Reference [31] finds phases of $\delta_{K^{*-}\pi^+} = (109 \pm 9)^\circ$ and $\delta_{\bar{K}^0\rho^0} = (-123 \pm 12)^\circ$ with respect to the nonresonant amplitude.

(3) $D^0 \to \bar{K}^0\pi^0\pi^0$ has two identical $\bar{K}^{*0}\pi^0$ bands which should interfere constructively with one another.

(4) $D^+ \to \bar{K}^0\pi^+\pi^0$ contributes to $\bar{K}^{*0}\pi^+$ and $\bar{K}^0\rho^+$. The amplitude triangles predict that (a) all the $\bar{K}\rho$ amplitudes are relatively real, and (b) the relative phase between the $\bar{K}^{*0}\pi^+$ and $K^{*-}\pi^+$ amplitudes (cf. Fig. 4) is

$$\delta_{\bar{K}^{*0}\pi^+,K^{*-}\pi^+}$$

$$= \cos^{-1} \frac{\Gamma(\bar{K}^{*0}\pi^+) + \Gamma(\bar{K}^-\pi^+) - 2\Gamma(\bar{K}^{*0}\pi^0)}{2|\mathcal{A}(\bar{K}^{*0}\pi^+)\mathcal{A}(K^{*-}\pi^+)|}$$

$$= (98^{+14}_{-13})^\circ. \tag{24}$$
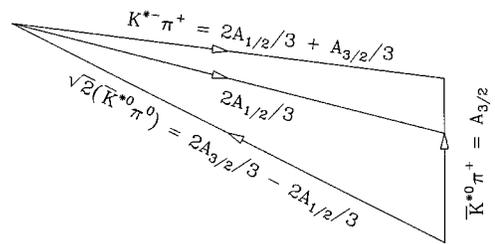
FIG. 4. Triangle of amplitudes in $D \to \bar{K}^*\pi$ decays. Subscripts on amplitudes denote total isospin.

These are tested by Mark III data on the $D^+ \to \bar{K}^0 \pi^+ \pi^0$ final state. One must combine the results $\delta_{\bar{K}^{*0}\pi^+, \bar{K}^0\rho^+} = (43 \pm 23)°$ from this final state with the previously mentioned phase $\delta_{K^{*-}\pi^+, K^-\rho^+} = (154 \pm 11)°$ from this experiment; the agreement seems good.

(5) $D^+ \to K^-\pi^+\pi^+$ has two identical $\bar{K}^{*0}\pi^+$ bands which should interfere constructively with one another.

Reference [33] contains some comments on the possibility that not all experiments quote phases with the same convention.

IV. PENGUIN-DOMINATED $b \to s$ PROCESSES

A. Charm-anticharm annihilation

A number of features of B decays suggest a possible role for enhanced charm-anticharm annihilation into noncharmed final states [39]:

(1) the semileptonic branching ratio $\mathcal{B}(B \to Xl\nu)$ is about 11% (vs a theoretical prediction of about 12%) [40];

(2) the number n_c of charmed particles per average B decay is about 1.1–1.2 vs a theoretical prediction of 1.2–1.3 [40];

(3) the inclusive branching ratio $\mathcal{B}(B \to \eta' X)$ appears large [41] in comparison with theoretical expectations [42];

(4) the exclusive branching ratio $\mathcal{B}(B \to K\eta')$ [41] appears to require an additional contribution [43] in comparison with the penguin contribution leading to $B^0 \to K^+\pi^-$ or $B^+ \to K^0\pi^+$.

A common source for these effects could be an enhanced rate for the subprocess $\bar{b} \to \bar{c}cs \to \bar{q}q\bar{s}$, where q stands for a light quark, e.g., through rescattering effects. These are inherently long-range and nonperturbative and could also be responsible for the overall enhancement of the $\bar{b} \to \bar{s}$ penguin transitions noted in Refs. [44]. Alternatives for points (3) and (4) which have been suggested include a large $c\bar{c}$ [45] or gluonic component in the η'. The former possibility is intriguing, but one must then ascribe the suppression of the decay $J/\psi \to \eta'\gamma$ to form factor effects.

If rescattering from the $\bar{b} \to \bar{c}c\bar{s}$ subprocess into states containing light quarks really is important, both the overall $\bar{b} \to \bar{s}$ penguin amplitude and a specific contribution [43] to $\bar{b} \to \bar{s} + (\eta, \eta')$ (to be mentioned below) could have strong phases very different from the tree amplitude contributing to $B \to K + X$ decays, raising the possibility of substantial CP-violating asymmetries whenever these amplitudes interfere with one another in a self-tagging B decay (such as $B^0 \to K^+\pi^-$). We shall now indicate where such effects are likely to be visible. (See also Refs. [46,47,48,49].)

B. Estimate of amplitudes and application to decays involving η'

In what follows we shall update an estimate [50] of the amplitudes contributing to the decays of $B \to PP$, where P is a light pseudoscalar meson. These amplitudes are denoted by t (tree), p (penguin), and s (singlet penguin). Color-suppressed amplitudes and electroweak penguin amplitudes [51,52,53,54] are neglected for simplicity. We shall be concerned with the relative strong phases of these amplitudes, which if large could lead to observable CP-violating asymmetries in several interesting final states. Amplitudes for strangeness-preserving processes will be unprimed, while those for strangeness-changing processes will be primed.

The weak phases for strangeness-preserving processes are $\arg(t) = \arg(V_{ub}^* V_{ud}) = \gamma$ and $\arg(p) = \arg(s) \simeq \arg(V_{tb}^* V_{td}) = -\beta$, so that the relative phase of t and p or s amplitudes is $\gamma + \beta = \pi - \alpha$. Here α, β, and γ are angles of the unitarity triangle as defined, for example, in Ref. [55]. (They are also referred to as ϕ_2, ϕ_1, and ϕ_3, respectively [56].) For strangeness-changing processes the expected phases are $\arg(t') = \arg(V_{ub}^* V_{us}) = \gamma$ and $\arg(p') = \arg(s') \simeq \arg(V_{tb}^* V_{ts}) = \pi$. Thus, the relative phase of t' and p' or s' amplitudes is γ (modulo π).

The tree amplitude t is expected to dominate strangeness-preserving $B \to PP$ decays such as $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^+\pi^-$. Although no conclusive evidence has been presented for these decays, one estimates [46], using factorization and the semileptonic process $B \to \pi l\nu$, that $\mathcal{B}(B^+ \to \pi^+\pi^0) \simeq (1/2)\mathcal{B}(B^0 \to \pi^+\pi^-) \simeq 4 \times 10^{-6}$. One can then use the relation $t' \simeq \lambda t$ to estimate the magnitude of the tree amplitude in strangeness-changing processes. Here $\lambda \simeq 0.2$ is the parameter introduced by Wolfenstein [57] to describe the hierarchy of CKM elements.

The penguin amplitude p' is expected to dominate strangeness-changing $B \to PP$ decays such as $B^0 \to K^+\pi^-$ and in particular $B^+ \to K^0\pi^+$ (which has no t' contribution). Differences between $\mathcal{B}(B^0 \to K^+\pi^-)$, $\mathcal{B}(B^+ \to K^0\pi^+)$, and $2\mathcal{B}(B^+ \to K^+\pi^0)$, important in more precise treatments which include effects of interference on rates [46,53], will be ignored here.

The coefficients of amplitudes in each decay process are given in Ref. [50]. Using the most recent rates for $B \to PP$ decays [46,58], we find the results shown in Table V. These deserve several comments.

(1) The s' amplitude is needed in order to properly describe the large rate [41] $\mathcal{B}(B \to K\eta') = (69 \pm 12) \times 10^{-6}$. Here we have averaged the values quoted for charged and neutral B decays. If the s' amplitude interferes constructively with p', it does not have to be as large in magnitude as p', as one sees by comparing the $|p'|^2$ rate for $B \to K\eta'$ in Table V with the $|s'|^2$ rate from column (a) of the same table. The weak phases of s' and p' are expected to be the same, aside from possible small electroweak penguin effects [52]. The strong phases of these two amplitudes could well be equal as well if they are both dominated by a large imaginary part associated with the annihilation of a $c\bar{c}$ pair into light quarks. Such a predominantly imaginary amplitude is one possible interpretation of the large final-state phases [12,13] in certain J/ψ hadronic decays which were discussed in Sec. II.

(2) The possibility for large CP-violating asymmetries exists whenever two weak amplitudes a_1 and a_2 [cf. Eq. (3)] are not too dissimilar in magnitude and the sines of both their weak phase difference $\phi_1 - \phi_2$ and their strong phase difference $\delta_1 - \delta_2$ are close to 1. In Table VI we identify a few of these interesting cases.

TABLE V. Summary of predicted contributions to selected $\Delta S = 0$ decays of B mesons. Rates are quoted in branching ratio units of 10^{-6}. Rates in italics are assumed inputs.

$\Delta S = 0$ Decay	$|t|^2$ rate	$|p|^2$ rate	$|s|^2$ [a]	rate [b]
$B^+ \to \pi^+ \pi^0$	*4*	0	0	0
$\to \pi^+ \eta$	2.7	1.0	0.09	0.3
$\to \pi^+ \eta'$	1.3	0.5	0.7	2.4
$B^0 \to \pi^+ \pi^-$	*8*	0.7	0	0

$|\Delta S = 1|$ Decay	$|t'|^2$ rate	$|p'|^2$ rate	$|s'|^2$ [b] [a]	rate [b]
$B^+ \to K^0 \pi^+$	0	*14*	0	0
$\to K^+ \pi^0$	0.2	7	0	0
$\to K^+ \eta$	0.13	≈ 0	1.7	6
$\to K^+ \eta'$	0.07	21	14	48
$B^0 \to K^+ \pi^-$	0.4	*14*	0	0
$\to K^0 \pi^0$	0	7	0	0
$\to K^0 \eta$	0	≈ 0	1.7	6
$\to K^0 \eta'$	0	21	14	48

[a]Constructive interference between p' and s' amplitudes assumed in $B^+ \to K^+ \eta'$.

[b]No interference between p' and s' amplitudes assumed in $B^+ \to K^+ \eta'$.

Although the t' amplitude in $B^+ \to K^+ \pi^0$ and $B^0 \to K^+ \pi^-$ processes is expected to be considerably smaller than the dominant p' amplitude, it can have a noticeable effect on the asymmetry if the strong phase difference is large. When the asymmetries in these two processes are combined, one may even be able to see an effect with present or modestly improved statistics [46]. The asymmetries in $B^+ \to K^+ \pi^0$ and $B^0 \to K^+ \pi^-$ are expected to be highly correlated [46,47].

To summarize, we are suggesting the prospect of a large strong phase shift difference $\delta_1 - \delta_2$ in certain two-body decays of B mesons to pairs of light pseudoscalar mesons, when one of the weak amplitudes (p, p', s, or s') has a large strong phase difference with respect to the other (t or t'). Such a phase may arise as a result of strong absorptive effects in rescattering of $c\bar{c}$ to light quarks. Although a perturbative calculation at the quark level [10] gives a small final-state phase, the possibility that it could be larger (even maximal, i.e., near $\pi/2$) was suggested some time ago [59].

TABLE VI. Examples of possible direct CP asymmetries in B decays.

Process	Interfering amplitudes	Relative weak phase	Maximum asymmetry
$B^+ \to \pi^+ \eta$	t,p	$\pi - \alpha$	$\sqrt{3/4}$
$B^+ \to \pi^+ \eta'$	t,s	$\pi - \alpha$	1
$B^+ \to K^+ \pi^-$	p',t'	γ	0.34
$B^0 \to K^+ \pi^-$	p',t'	γ	0.34

The rescattering of $c\bar{c}$ to light final states can enhance the $\bar{b} \to \bar{s}$ penguin amplitude without affecting its weak phase, which remains real: $\arg(V_{cb}^* V_{cs}) = 0$ vs. $\arg(V_{tb}^* V_{ts}) = \pi$.

C. Annihilation of light quarks

If the $\bar{b} \to \bar{s}$ penguin amplitude receives important contributions from the tree subprocess $\bar{b} \to \bar{u}u\bar{s}$, followed by rescattering to another final state (such as $\bar{d}d\bar{s}$), the estimate of the weak phase of the amplitude for $B^+ \to K^0 \pi^+$ may be called into question [11]. Normally one expects this process to have a weak phase of π or zero, so that there should be only a very small CP-violating difference between the rates for $B^+ \to K^0 \pi^+$ and $B^- \to \bar{K}^0 \pi^-$. This difference, in the absence of rescattering, would be due entirely to the process in which the $\bar{b}$ and spectator u in a B^+ annihilate one another through a virtual W which then produces $K^0 \pi^+$. Such an amplitude is expected to be suppressed by a factor of f_B/m_B in comparison with the dominant ones in which the spectator quark does not participate.

The decay $B^0 \to K^+ K^-$ is particularly sensitive to spectator quark effects, since the B^0 contains a d quark which is not present in the final state [22,60]. It must occur through the process $\bar{b}d \to \bar{u}u$, in which the $\bar{u}u$ pair either fragments into $K^+ K^-$ directly or annihilates into a multigluon state which then materializes as $K^+ K^-$. Alternatively, it can be fed by rescattering from such final states as $B^0 \to M_1^+ M_2^-$, where M_i are nonstrange mesons such as π and ρ. Thus, a good way to gauge the effects of this rescattering is to measure the branching ratio for $B^0 \to K^+ K^-$. If it exceeds the value of a few times 10^{-8}, one must take rescattering effects seriously.

Another method which has been proposed to estimate rescattering effects is to study the rate and CP-violating asymmetry for the decay $B^+ \to \bar{K}^0 K^+$, whose amplitudes are related to those in $B^+ \to K^0 \pi^+$ by flavor SU(3) [11]. Specifically, the penguin amplitude in $B^+ \to \bar{K}^0 K^+$ should be suppressed by $|V_{td}/V_{ts}| = \mathcal{O}(\lambda) \approx 1/5$ with respect to that in $B^+ \to K^0 \pi^+$, while the corresponding annihilation (or rescattering) amplitude should be *enhanced* by $|V_{ud}/V_{us}| = 1/\lambda$. Our discussion indicates that both the (suppressed) penguin amplitude and the (enhanced) rescattering amplitude in $B^+ \to \bar{K}^0 K^+$ may have the same final-state phase characteristic of a highly absorptive process, so that a CP-violating difference between $\Gamma(B^+ \to \bar{K}^0 K^+)$ and $\Gamma(B^- \to K^0 K^-)$ may not be visible even if the rescattering process is playing an important role. One then falls back on the proposed enhancement of the total $B^+ \to \bar{K}^0 K^+$ decay rate, which would require a substantial rescattering contribution to be observable, or—better, in our opinion—the observation of the rare process $B^0 \to K^+ K^-$ to indicate the magnitude of rescattering effects.

V. B DECAYS TO CHARMED FINAL STATES

A. Decays to $\bar{D}\pi$, $\bar{D}^*\pi$, $\bar{D}\rho$, $\bar{D}^*\rho$

The pattern of B decays to charmed final states has important differences with respect to the corresponding pattern

for D decays to strange states. First of all, the relative phase of color-suppressed (C) and color-favored (T) amplitudes is different from that in charm decays [24]. Second, one cannot evaluate the final-state phases associated with rescattering effects, since these effects seem so small.

We may perform an isospin decomposition similar to that in Sec. III for charm decays by noting that the fundamental $\bar{b} \to \bar{c} u \bar{d}$ subprocess responsible for $B \to \bar{D}^{(*)} + X$ decays has $\Delta I = \Delta I_3 = 1$. Thus, when X is an $I = 1$ meson (e.g., π or ρ), there will again be two isospin amplitudes. For $\bar{B} \to D \pi$ decays we may then write

$$\mathcal{A}(B^+ \to \bar{D}^0 \pi^+) = A_{3/2},$$

$$\mathcal{A}(B^0 \to D^- \pi^+) = \frac{2}{3} A_{1/2} + \frac{1}{3} A_{3/2},$$

$$\mathcal{A}(B^0 \to \bar{D}^0 \pi^0) = -\frac{\sqrt{2}}{3} A_{1/2} + \frac{\sqrt{2}}{3} A_{3/2}. \quad (25)$$

These amplitudes again satisfy a triangle relation

$$\mathcal{A}(\bar{D}^0 \pi^+) = \mathcal{A}(D^- \pi^+) + \sqrt{2} \mathcal{A}(\bar{D}^0 \pi^0). \quad (26)$$

For the $\bar{D}^* \rho$ amplitudes, which are characterized by three partial waves with orbital angular momenta $l = 0$, 1, and 2, these relations hold separately for each partial wave. In what follows we shall assume a single partial wave to dominate the process when discussing amplitude relations, but will see in Sec. V B that this is an oversimplification.

The magnitude of the $I = 3/2$ amplitude is obtained from the $B^+ \to \bar{D}^0 \pi^+$ partial width: $|A_{3/2}|^2 = \Gamma(\bar{D}^0 \pi^+)$. The magnitude of the $I = 1/2$ amplitude is obtained from the combination

$$|A_{1/2}|^2 = \frac{3}{2} [\Gamma(D^- \pi^+) + \Gamma(\bar{D}^0 \pi^0)] - \frac{1}{2} \Gamma(\bar{D}^0 \pi^+). \quad (27)$$

The relative phase δ_I between isospin amplitudes is given by

$$\cos \delta_I = \frac{3\Gamma(D^- \pi^+) + \Gamma(\bar{D}^0 \pi^+) - 6\Gamma(\bar{D}^0 \pi^0)}{4|A_{1/2} A_{3/2}|}. \quad (28)$$

When only an upper bound on the color-suppressed rate is available, a useful upper bound [24] on δ_I is

$$\sin^2 \delta_I \leq 9\Gamma(\bar{D}^0 \pi^0)/2\Gamma(\bar{D}^0 \pi^+). \quad (29)$$

Similar expressions hold for $\bar{D}^* \pi$, $\bar{D} \rho$, and $\bar{D}^* \rho$ decays.

Decomposing the decay amplitudes in terms of tree (T), color-suppressed (C), and exchange (E) amplitudes [22], one finds expressions in correspondence with those in Sec. III:

$$\mathcal{A}(\bar{D}^0 \pi^+) = T + C, \quad \mathcal{A}(D^- \pi^+) = T + E,$$

$$\mathcal{A}(\bar{D}^0 \pi^0) = (C - E)/\sqrt{2}. \quad (30)$$

TABLE VII. B^+ and B^0 branching ratios and decay rates.

Mode	Branching ratio (%)	Decay rate ($\times 10^8$ s^{-1})
	B^+ decays	
$\bar{D}^0 \pi^+$	0.53 ± 0.05	32 ± 3
$\bar{D}^{*0} \pi^+$	0.46 ± 0.04	28 ± 2.5
$\bar{D}^0 \rho^+$	1.34 ± 0.18	81 ± 11
$\bar{D}^{*0} \rho^+$	1.55 ± 0.31	94 ± 19
	$B^0 \to (-+)$ decays	
$D^- \pi^+$	0.30 ± 0.04	19.2 ± 2.6
$D^{*-} \pi^+$	0.276 ± 0.021	17.7 ± 1.4
$D^- \rho^+$	0.79 ± 0.14	51 ± 9
$D^{*-} \rho^+$	0.67 ± 0.33	43 ± 21
	$B^0 \to (00)$ decays	
$\bar{D}^0 \pi^0$	<0.012	<0.77
$\bar{D}^{*0} \pi^0$	<0.044	<2.8
$\bar{D}^0 \rho^0$	<0.039	<2.5
$\bar{D}^{*0} \rho^0$	<0.056	<3.6

The amplitude E is used here to describe either an exchange subprocess $\bar{b}d \to \bar{c}u$, or rescattering from the tree-dominated process $\bar{b}d \to \bar{c}u\bar{d}d$ through $d\bar{d}$ annihilation into a flavor-SU(3) singlet state. As in Sec. III, we neglect electroweak penguins.

Here, as in the case of D decays, the set T, C, and E is overcomplete, so we cannot extract independent information on the magnitude of E. In principle, one could perform a calculation based on the factorization assumption, as mentioned in Sec. III, to relate the tree contribution T in, e.g., $B^0 \to D^- \pi^+$ to that in a semileptonic decay process such as $B^0 \to D^- l^+ \nu_l$. One already knows that this calculation works approximately [25,26,61]. It is also likely that C and T are relatively real, since neither involves the highly absorptive annihilation process described by E.

The value of E is expected to be quite small for a couple of reasons. First, estimates based on either rescattering or interaction with the spectator quark suggest that E will be much smaller in the B system than in the charm system. Second, whereas $\tau(D^+)/\tau(D^0) \simeq 2.5$, indicating the importance of spectator interactions or long-distance physics for charm, the corresponding ratio for B mesons is much closer to 1, since [16] $\tau(B^+) = (1.65 \pm 0.04) \times 10^{-12}$ s while $\tau(B^0) = (1.56 \pm 0.04) \times 10^{12}$ s. This implies that we will have some difficulty determining the phase of E relative to that of C and T. One will have to determine the relative contributions of C and T (through calculations such as those suggested for charm decays in Sec. III B), and the small E contribution, if it is present, will then have to be extracted. At present this is not possible because none of the color-suppressed decays $B^0 \to (00)$ has been observed [16,62].

The relevant branching ratios and rates [16] are summarized in Table VII. In all cases the amplitude relations degenerate into a nearly straight line, since the square roots of the rates in Table VII all are consistent with $[\Gamma(0+)]^{1/2} - [\Gamma(-+)]^{1/2} = [2\Gamma(00)]^{1/2}$. This point is emphasized in

TABLE VIII. Comparison of amplitudes for $B \to \bar{D}^{(*)} + (\pi, \rho)$ decays.

Mode	$[\Gamma(0+)]^{1/2} - [\Gamma(-+)]^{1/2}$ $(\times 10^4 \text{ s}^{-1/2})$	$[2\Gamma(00)]^{1/2}$ $(\times 10^4 \text{ s}^{-1/2})$	δ_I (max) (degrees)	$[\Gamma(0+)]^{1/2} / [\Gamma(-+)]^{1/2}$
$\bar{D}\pi$	1.3 ± 0.4	<1.2	19	1.29 ± 0.11
$\bar{D}^*\pi$	1.1 ± 0.3	<2.4	46	1.25 ± 0.08
$\bar{D}\rho$	1.9 ± 0.9	<2.2	25	1.27 ± 0.14
$\bar{D}^*\rho$	3.1 ± 1.9	<2.7	40	1.48 ± 0.40

Table VIII, where we also quote Suzuki's limits [14] on the relative phases of $I = 1/2$ and $I = 3/2$ amplitudes [63]. Comparison of the second and third columns of Table VIII allows one to see how far above the lower isospin bound each (00) color-suppressed mode lies. The decay $B^0 \to \bar{D}^0 \pi^0$ should appear at a level not much below its present upper experimental bound.

The possibility of a small E contribution with a highly absorptive phase cannot be excluded. Present data are consistent with T and C contributions with no relative phase. If E is negligible and C is real relative to T, each process is characterized by $|C + T|/|T| = [\Gamma(0+)]^{1/2}/[\Gamma(-+)]^{1/2}$. The entries in the last column of Table VIII are consistent with a universal value of $C/T = 0.27 \pm 0.06$.

B. Relative phases of $B \to VV$ amplitudes

The CLEO Collaboration [64] has presented evidence in the decays $B^0 \to D^{*-}\rho^+$ and $B^+ \to \bar{D}^{*0}\rho^+$ for complex phases between helicity amplitudes, and for the presence of more than one partial wave in these decays. The helicity amplitudes A_0 and $A_{\pm 1}$ for $B \to VV$ decays are expressible in terms of $l = 0$, 1, and 2 partial waves S, P, and D as [65]

$$A_{\pm 1} = \sqrt{\frac{1}{3}}S \pm \sqrt{\frac{1}{2}}P + \sqrt{\frac{1}{6}}D, \quad A_0 = -\sqrt{\frac{1}{3}}S + \sqrt{\frac{2}{3}}D. \tag{31}$$

Here the amplitudes are normalized such that $|A_0|^2 + |A_1|^2 + |A_{-1}|^2 = |S|^2 + |P|^2 + |D|^2 = 1$. While a full analysis of the CLEO results, which in any case are preliminary, is beyond the scope of this note, we point out several interesting features.

(1) The fraction of the decay which is longitudinal, $|A_0|^2$, is about 0.86 in both $B^0 \to D^{*-}\rho^+$ and $B^+ \to \bar{D}^{*0}\rho^+$, indicating that no individual partial wave dominates the decay.

(2) For $B^0 \to D^{*-}\rho^+$ the helicity amplitudes A_1 and A_{-1} are unequal (and have unequal phases), indicating the presence of a P wave as well as S and/or D wave components. Only the amplitude A_1 has a nontrivial phase with respect to A_0.

(3) For $B^+ \to \bar{D}^{*0}\rho^+$, the amplitudes A_1 and A_{-1} are consistent with being equal, indicating that no P-wave component may be needed. However, in this case both A_1 and A_{-1} have nontrivial phases with respect to A_0.

These results may indicate the presence of nontrivial final-state interactions in the $B \to \bar{D}^*\rho$ decays, since such

relative phases in helicity amplitudes cannot arise at the level of weak amplitudes. The dominant subprocess in all these decays should be $\bar{b} \to \bar{c}u\bar{d}$, with a vanishing weak phase.

VI. SUMMARY

We have reviewed a number of cases, many of which were first pointed out by Suzuki [12,13,14], in which nontrivial final-state interactions manifest themselves in decay processes involving the release of up to a few GeV of energy. These include J/ψ decays to pairs of light mesons, charmed meson decays, and possibly $B \to \bar{D}^*\rho$. We have argued that such large final-state phases may also occur in penguin processes involving $\bar{b} \to \bar{s}$ transitions, especially those in which flavor-singlet mesons such as η' are produced. Such final-state phases may be useful in searching for direct CP violation in decays such as $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$. Our conclusion regarding the possibility of large final-state phases is more optimistic than that of Ref. [66], where typical strong phases of order 20° have been estimated, as a result of our conjecture that the $c\bar{c}$ annihilation process contributing to the penguin amplitude can be highly absorptive.

A number of open experimental questions remain. These can shed light on whether there is a universal pattern giving rise to large final-state interactions, or whether these effects must be studied on a case-by-case basis.

(1) Although large final-state interactions have been demonstrated in J/ψ decays to VP [12] and PP [13] final states, we do not yet know whether the same is true for ψ' decays. Observation of the process $\psi' \to K^{*+}K^- + $ c.c. and reduction in errors on the branching ratios for $\psi' \to K^{*0}\bar{K}^0 + $ c.c. and $\psi' \to \omega\pi^0$ would help clarify this question.

(2) We cannot yet choose between a resonant and nonresonant interpretation of the large relative phase between $I = 1/2$ and $I = 3/2$ amplitudes in $D \to \bar{K}\pi$ and $D \to \bar{K}^*\pi$ decays. Although a $J^P = 0^+$ resonance decaying to $\bar{K}\pi$ has been seen near the D mass [37], there does not yet exist a candidate for a corresponding 0^- resonance decaying to $\bar{K}^*\pi$. Moreover, such a resonance should not couple appreciably to $\bar{K}\rho$ if the resonant interpretation is correct. By comparing Figs. 3 and 4, we see that such a resonance should be more prominent in the $\bar{K}^*\pi$ channel than the 0^+ resonance is in the $\bar{K}\pi$ channel, since its enhancement of the $I = 1/2$ amplitude relative to the $I = 3/2$ amplitude is greater. The absence of an appreciable resonant or rescattering enhance-

ment in the $\bar{K}\rho$ channel may provide a clue to the space-time properties of the enhancement mechanism.

(3) A number of tests of the factorization hypothesis in charmed particle decays [23,24,61] are available. With new large samples of charmed particle decays becoming available from several sources (e.g., the CLEO detector at Cornell and the FOCUS Collaboration at Fermilab), it might be worth re-examining two- and three-body D decays to see if these relations continue to hold.

(4) Rare decays of B mesons, as pointed out also elsewhere [11], can shed light on at least the magnitude, if not the phase, of final-state interaction effects. Such effects would be manifested, for example, as (a) an observable CP-violating difference between the branching ratios for $B^+ \to K^0\pi^+$ and $B^- \to \bar{K}^0\pi^-$, (b) an enhancement of the rate for $B^+ \to K^+\bar{K}^0$ and its charge-conjugate, and a possible CP-violating asymmetry in these two rates, and (c) a branching ratio for $B^0 \to K^+K^-$ above the level of a few parts in 10^8. We have pointed out that if large final-state phases have a universal nature as a result of highly absorptive processes, the CP asymmetries in $B^+ \to K^0\pi^+$ and $B^+ \to K^+\bar{K}^0$ may not be so large, and the rate enhancements in $B^+ \to K^+\bar{K}^0$ and $B^0 \to K^+K^-$ may be a preferable means of displaying large final-state interactions.

(5) The question of large final-state phases due to rescattering in B decays to charmed particles remains open. Such phases could arise as a result of annihilation of light-quark pairs. More information on such processes will be forthcoming once the color-suppressed processes $B^0 \to [\bar{D}^{(*)0} + (\pi^0 \text{ or } \rho^0)]$ have been observed.

Note added in proof. The investigation of final-state phases in charmed meson two-body nonleptonic decays mentioned at the end of Sec. III B has now been performed [67].

ACKNOWLEDGMENTS

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