B decays to charmless VP final states

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The CLEO Collaboration has now observed the decays $B^+\to\omega\pi^+$ and $B\to\omega K^+$ with branching ratios of $(1.1^{+0.6}_{-0.5}\pm0.2)\times10^{-5}$ and $(1.5^{+0.7}_{-0.6}\pm0.3)\times10^{-5}$, respectively. These are the first reported decays to charmless final states involving a vector (V) and a pseudoscalar (P) meson. The implications of these decays for others of B mesons to charmless VP final states are explored. In a model-independent approach, using only flavor SU(3) symmetry, several tests are proposed for an anticipated hierarchy among different contributions to decay amplitudes. [S0556-2821(98)00905-9]

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I. INTRODUCTION

The CLEO Collaboration [1] has now observed the decays $B^+\to\omega\pi^+$ and $B\to\omega K^+$ with branching ratios of $(1.1^{+0.6}_{-0.5}\pm0.2)\times10^{-5}$ (2.9σ) and $(1.5^{+0.7}_{-0.6}\pm0.3)\times10^{-5}$ (4.3σ), respectively. These are the first reported decays of B mesons to charmless final states involving a vector (V) and a pseudoscalar (P) meson. VP final states may be crucial in studies of CP violation in B decays [2].

We have previously applied flavor SU(3) symmetry [3–5] to decays of the form $B\to PP$ [6–13], and made some preliminary remarks about VP decays in Refs. [8] and [13]. In the latter paper relations are defined between SU(3) amplitudes and quark diagrams for VP decays. The observation of the $\omega\pi^+$ and ωK^+ modes and the existence of limits on other VP modes at levels close to those expected [14] make an updated analysis relevant at this time. The 2.9σ level of the $\omega\pi^+$ signal requires that we regard it as preliminary.

We decompose amplitudes for $B\to VP$ decays into linear combinations of reduced matrix elements in Sec. II. Applications of the relations implied by these decompositions, suggesting a variety of tests for an anticipated hierarchy among different contributions, are discussed in Sec. III. Our results are compared with attempts to calculate decay modes *a priori* with the help of specific models in Sec. IV. We conclude (with a brief summary of experimental prospects) in Sec. V.

II. SU(3) DECOMPOSITION

In Tables I and II we list the VP modes of nonstrange B mesons for strangeness-preserving and strangeness-changing decays, respectively. Our notation is as follows:

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(1) As a language equivalent to flavor SU(3), we employ an overcomplete set of quark diagrams [5], which we denote by T (tree), C (color suppressed), P (QCD penguin), S [additional penguin contribution involving flavor-SU(3)-singlet mesons, called P_1 in Ref. [10]], E (exchange), A (annihilation) and PA (penguin annihilation). The last three amplitudes, in which the spectator quark enters into the decay Hamiltonian, are expected to be suppressed by f_B/m_B (f_B ≈ 180 MeV) and may be neglected to a good approximation. The presence of higher-order electroweak penguin contributions [15] introduces no new SU(3) amplitudes, and in terms of quark graphs merely leads to a substitution [8,10]

$$T\to t\equiv T+P^C_{EW},\quad C\to c\equiv C+P_{EW},$$

$$P\to p\equiv P-\frac{1}{3}P^C_{EW},\quad S\to s\equiv S-\frac{1}{3}P_{EW},\qquad(1)$$

where P_{EW} and P^C_{EW} are color-favored and color-suppressed electroweak penguin amplitudes.

(2) We use the phase conventions of Ref. [6] for pseudoscalar mesons, the mixing assumption $\eta=(s\bar{s}-u\bar{u}-d\bar{d})/\sqrt{3}$ and $\eta'=(u\bar{u}+d\bar{d}+2s\bar{s})/\sqrt{6}$, and the corresponding phase conventions for vector mesons with $\omega=(u\bar{u}+d\bar{d})/\sqrt{2}$ and $\phi=s\bar{s}$.

(3) We denote strangeness-preserving ($\Delta S=0$) amplitudes by unprimed letters and strangeness-changing ($|\Delta S|=1$) amplitudes by primed letters.

(4) The suffix on each amplitude denotes whether the spectator quark is included in a pseudoscalar (P) or vector (V) meson.

(5) Each decay amplitude involves positive or negative integer coefficients multiplying the indicated reduced amplitudes and divided by a common denominator factor.

TABLE I. $\Delta S=0$ $B\to VP$ decays. Coefficients of amplitudes are to be divided by the denominator factor.

	Denominator	t_P	t_V	c_P	c_V	p_P	p_V	s_P	s_V
$B^+\to\rho^+\pi^0$	$-\sqrt{2}$	1			1	1	-1		
$\rho^0\pi^+$	$-\sqrt{2}$		1	1		-1	1		
$\omega\pi^+$	$\sqrt{2}$		1	1		1	1	2	
$\phi\pi^+$	1							1	
$\rho^+\eta$	$-\sqrt{3}$	1			1	1	1		1
$\rho^+\eta'$	$\sqrt{6}$	1			1	1	1		4
$K^{*+}\overline{K^0}$	1						1		
$\overline{K^{*0}}K^+$	1					1			
$B^0\to\rho^-\pi^+$	-1		1				1		
$\rho^+\pi^-$	-1	1				1			
$\rho^0\pi^0$	2			-1	-1	1	1		
$\omega\pi^0$	2			1	-1	1	1	2	
$\phi\pi^0$	$\sqrt{2}$							1	
$\rho^0\eta$	$-\sqrt{6}$			-1	1	1	1		1
$\rho^0\eta'$	$2\sqrt{3}$			-1	1	1	1		4
$\omega\eta$	$-\sqrt{6}$			1	1	1	1	2	1
$\omega\eta'$	$2\sqrt{3}$			1	1	1	1	2	4
$\phi\eta$	$-\sqrt{3}$							1	
$\phi\eta'$	$\sqrt{6}$							1	
$K^{*0}\overline{K^0}$	1						1		
$\overline{K^{*0}}K^0$	1					1			

III. APPLICATIONS

A. Hierarchies of amplitudes

One can immediately identify certain amplitudes likely to be most important in $B\to VP$ decays. In the corresponding PP decays (which may be denoted by similar amplitudes without the subscripts), the amplitudes are expected to obey an approximate hierarchy [6–8,12,16]. The process $B^0\to K^+\pi^-$ is observed with a branching ratio somewhat in excess of 10^{-5}, while $B^0\to\pi^+\pi^-$ is expected to have a branching ratio not vastly different from this. Thus we deduced in previous work that $|t|\simeq|p'|$, while $|p/t|\simeq|t'/p'|\simeq\lambda$, where $\lambda\equiv V_{us}\simeq 0.22$. We do not have an estimate for $|c/t|$ or $|c'/t'|$. We expect $|c/t|$ to be small on the basis of color-suppression arguments. However, $|c'/t'|$ may be larger due to the electroweak penguin term in c' [see Eq. (1)]. The large branching ratios for $B^+\to K^+\eta'$ (about 7×10^{-5}) and $B^0\to K^0\eta'$ (about 5×10^{-5}) [17] indicate the importance of the s' amplitude at a level comparable to that of p' [12,18].

A similar hierarchy appears to apply to the VP decays. The fact that the $B^+\to\omega\pi^+$ and $B^+\to\omega K^+$ branching ratios are comparable to one another and each of order 10^{-5} indicates that the dominant contribution to $\omega\pi^+$ is most likely t_V, while the dominant contribution to ωK^+ is most likely p'_V. We expect the s'_P contribution to be relatively unimportant; this contribution would involve a coupling of the ω and ϕ which violated the Okubo-Zweig-Iizuka (OZI) rule favoring connected quark diagrams. Such couplings are probably much more important for η and η' than for vector mesons. Specifically, the penguin amplitude s'_V, coupling to the flavor SU(3) singlet component of the η and and η', can be as large as or even larger than p'_V. A similar situation seems to hold in decays to two light pseudoscalar mesons [12].

B. Tests for smallness of amplitudes

How can one learn more about which VP amplitudes are important? One way of using the tables is to compare charged B decays and neutral B decays to each other. This can teach us something about the magnitudes of some of the amplitudes. Consider, for instance, the eight pairs of $|\Delta S|=1$ processes listed in Table II. The following approximate amplitude equalities test the smallness of certain contributions. The relations between B^+ and B^0 amplitudes are independent of SU(3) breaking. In each case we list only the final state.

(1) Smallness of $c'_{P,V}$:

$$\rho^+K^0\approx\sqrt{2}(\rho^0K^0),\qquad \sqrt{2}(\rho^0K^+)\approx\rho^-K^+,$$

$$K^{*0}\pi^+\approx\sqrt{2}(K^{*0}\pi^0),\qquad \sqrt{2}(K^{*+}\pi^0)\approx K^{*+}\pi^-. \quad (2)$$

The $c'_{P,V}$ amplitudes contain color-favored electroweak penguin terms which may not be negligible [see Eq. (1) and Ref. [15]], and indeed provide important contributions in *a priori* calculations to be discussed in Sec. IV.

(2) Smallness of $t'_{P,V}$:

$$\omega K^+\approx\omega K^0,\quad K^{*+}\eta\approx K^{*0}\eta,\quad K^{*+}\eta'\approx K^{*0}\eta'. \quad (3)$$

(3) Smallness of s'_P:

$$-\rho^0K^+\approx\omega K^+,\quad K^{*0}\pi^+\approx\phi K^+. \quad (4)$$

TABLE II. $|\Delta S|=1$ $B\to VP$ decays. Coefficients of amplitudes are to be divided by the denominator factor.

	Denominator	t'_P	t'_V	c'_P	c'_V	p'_P	p'_V	s'_P	s'_V
$B^+\to\rho^+K^0$	1						1		
ρ^0K^+	$-\sqrt{2}$		1	1			1		
$K^{*0}\pi^+$	1					1			
$K^{*+}\pi^0$	$-\sqrt{2}$	1			1	1			
ωK^+	$\sqrt{2}$		1	1			1	2	
ϕK^+	1					1		1	
$K^{*+}\eta$	$-\sqrt{3}$	1			1	1	-1		1
$K^{*+}\eta'$	$\sqrt{6}$	1			1	1	2		4
$B^0\to\rho^-K^+$	-1		1				1		
ρ^0K^0	$\sqrt{2}$			-1			1		
$K^{*+}\pi^-$	-1	1				1			
$K^{*0}\pi^0$	$\sqrt{2}$				-1	1			
ωK^0	$\sqrt{2}$			1			1	2	
ϕK^0	1					1		1	
$K^{*0}\eta$	$-\sqrt{3}$				1	1	-1		1
$K^{*0}\eta'$	$\sqrt{6}$				1	1	2		4

The first relation is sensitive to any breakdown of nonet symmetry (unequal decay constants for ρ and ω mesons). The second relation is sensitive to SU(3)-breaking effects since it involves comparing an amplitude with nonstrange quark pair production to one with strange quark pair production; the form factors are also likely to differ [13].

In addition, a number of approximate triangle relations hold, such as

$$\sqrt{2}(\rho^+K^0)\approx\rho^0K^0+\omega K^0, \tag{5}$$

all of whose sides have a p'_V contribution, and so the decay rates may be significant. The shape of the amplitude triangle may tell us about the relative magnitudes and phases of c'_P and p'_V. Since we expect c'_P to be smaller than p'_V, this triangle will be a ''squashed'' one.

(4) The last relation among the eight pairs of amplitudes, $\phi K^+=\phi K^0$, follows from isospin. This equality neglects final state rescattering from intermediate states such as ρK, ωK, and $K^*\pi$

Assuming that both s'_P and c'_P are small, one also finds $\rho^0K^0\approx\omega K^0$. Lipkin [18] has pointed out that if s'_P is small [as checked, for example, by relations such as Eq. (4)], but if the $B^0\to\rho^0K^0$ and $B^0\to\omega K^0$ rates are *unequal*, then both p'_V and c'_P amplitudes must be present, and they are close enough in amplitude for interference to be observed. Whether this enhances the possibility of observing direct CP violation [18] remains an open question. The most likely source of a contribution to c'_P is an electroweak penguin amplitude with the same weak phase as p'_V, and so a direct CP asymmetry is unlikely in the neutral decays. In the more readily observed charged decays $B^+\to(\rho^0,\omega)K^+$, one would need interference between t'_P and p'_V to see a CP asymmetry. In our approach one cannot infer anything about t'_V from c'_P.

The $\Delta S=0$ amplitudes do not exhibit simple isospin relations which test the smallness of some amplitudes. Still, one can make the following observations about large and small amplitudes:

(1) The largest amplitudes are expected to be t_P, t_V. Therefore, the following 7 processes are expected to have the largest rates: $\rho^+\pi^0$, $\rho^0\pi^+$, $\omega\pi^+$, $\rho^+\eta$, $\rho^+\eta'$, $\rho^-\pi^+$, and $\rho^+\pi^-$.

(2) Smaller decay rates (equal in B^+ and B^0 decays) measure different kinds of penguin amplitudes:

p_P is measured in $\overline{K^{*0}}K^+=\overline{K^{*0}}K^0$.

p_V is measured in $K^{*+}\overline{K^0}=K^{*0}\overline{K^0}$.

s_P is measured in $\phi\pi^+=\sqrt{2}(\phi\pi^0)=-\sqrt{3}(\phi\eta)=\sqrt{6}(\phi\eta')$.

s_V is measured by the combinations $\sqrt{6}(\rho^+\eta')+\sqrt{3}(\rho^+\eta)$, $2\sqrt{3}(\rho^0\eta')+\sqrt{6}(\rho^0\eta)$, and $2\sqrt{3}(\omega\eta')+\sqrt{6}(\omega\eta)$, implying rate relations if s_V is small.

C. Relations testing for presence or absence of s'_V

Whereas the amplitude p'_V can be measured directly in $B^+\to\rho^+K^0$, it is much more difficult to determine the amplitude s'_V contributing only to decays involving the η and η'. We recall that the presence of the corresponding sizable amplitude s' in $B\to PP$ decays was manifested by the particularly large $B\to K\eta'$ decay rate [12].

Several tests for the presence of the singlet amplitude s'_V can be constructed. s'_V is less likely to be small than s'_P, since the axial anomaly can affect η and η' flavor-singlet couplings [19]. A large corresponding singlet amplitude in $|\Delta S|=1$ $B\to PP$ decays was found to be needed to explain the observed $B\to K\eta'$ rate [12].

In the event that s'_V *is* negligible, several triangle relations hold among the amplitudes for $B^+\to\rho^0K^+$ and $B^+\to K^{*+}(\pi^0,\eta,\eta')$, and among the amplitudes for $B^0\to K^{*0}(\eta,\eta')$ and $B^0\to\rho^+K^0$. If we are willing, moreover, to neglect c'_V in comparison with other amplitudes, a set of triangle relations analogous to the above, but with the decays $B^0\to K^{*0}(\eta,\eta')$ replacing $B^+\to K^{*+}(\eta,\eta')$ and with $K^{*0}\pi^+$ replacing $-\sqrt{2}(K^{*+}\pi^0)$, should hold.

Under some circumstances, interference terms between contributions of different amplitudes to rates will cancel when suitable sums of rates are constructed. Thus, one finds that if s'_V can be neglected, the triangle relations mentioned above imply

$$\mathcal{B}(B^+\to K^{*+}\pi^0)+\mathcal{B}(B^+\to\rho^+K^0) = \mathcal{B}(B^+\to K^{*+}\eta)+\mathcal{B}(B^+\to K^{*+}\eta'). \quad (6)$$

Similarly, with c'_V small in addition, one finds

$$\mathcal{B}(B^+\to K^{*0}\pi^+)/2+\mathcal{B}(B^+\to\rho^+K^0) = \mathcal{B}(B^0\to K^{*0}\eta)+\mathcal{B}(B^0\to K^{*0}\eta'). \quad (7)$$

(Here and later we neglect phase space effects.) Both sides of these two relations contain contributions from the p'_V amplitude, which we expect to be significant. The failure of either of the above two equations to hold would indicate a significant s'_V contribution. In that case, we may proceed to determine s'_V as follows.

When the amplitude s'_V is not neglected, the triangle relations for B^+ decays discussed above are replaced by

$$-\sqrt{2}(K^{*+}\pi^0)-(\rho^+K^0)+s'_V=-\sqrt{3}(K^{*+}\eta), \quad (8)$$

$$-\sqrt{2}(K^{*+}\pi^0)+2(\rho^+K^0)+4s'_V=\sqrt{6}(K^{*+}\eta'). \quad (9)$$

Moreover, if c'_V can be neglected, one can write

$$(K^{*0}\pi^+)-(\rho^+K^0)+s'_V=-\sqrt{3}(K^{*0}\eta), \quad (10)$$

$$(K^{*0}\pi^+)+2(\rho^+K^0)+4s'_V=\sqrt{6}(K^{*0}\eta'). \quad (11)$$

In the complex plane, let $(\rho^+K^0)=(1,0)$ [so that all the amplitudes and phases in these relations are measured in units of (ρ^+K^0)]. Since only p'_V contributes to (ρ^+K^0), all the amplitudes will henceforth be given in terms of p'_V as the unit.

Let $-\sqrt{2}(K^{*+}\pi^0)=(a,b)$, $(K^{*0}\pi^+)=(c,d)$, and $s'_V=(e,f)$. Then, squaring the above four equations to obtain four rate relations, and constraining a^2+b^2 and c^2+d^2 using the rates for the decays $B^+\to K^{*+}\pi^0$ and $B^+\to K^{*0}\pi^+$, we have six equations in the six unknowns a,b,c,d,e,f. One is required to measure seven different decay rates, but all of them involve p'_V, so none of them should be very small.

D. Where does the spectator quark end up?

The distinction between amplitudes a_P or a'_P ($a\equiv t$, c, p, s) (in which the spectator quark is incorporated into a pseudoscalar meson) and a_V or a'_V (in which the spectator ends up in a vector meson) is responsible for the large number of reduced amplitudes in the VP case, as compared to the simpler PP decays. Some hint that these amplitudes may not have equal magnitudes is provided by the upper bound [1] $\mathcal{B}(B^+\to\phi K^+)<0.53\times10^{-5}$, as compared with $\mathcal{B}(B^+\to\omega K^+)=(1.5^{+0.7}_{-0.6}\pm0.3)\times10^{-5}$, implying $\mathcal{B}(B^+\to\phi K^+)/\mathcal{B}(B^+\to\omega K^+)<1$. The ϕK^+ amplitude is dominantly p'_P, while the ωK^+ amplitude is mainly $p'_V/\sqrt{2}$. If the p'_P and p'_V amplitudes were equal, we should have expected $\mathcal{B}(B^+\to\phi K^+)=2\mathcal{B}(B^+\to\omega K^+)$. The amplitude p'_V can be measured directly in $B^+\to\rho^+K^0$ and, neglecting c'_P, in $B^0\to\rho^0K^0$. To confirm that indeed $|p'_V|>|p'_P|$, it would be useful to compare p'_V measured in this way with p'_P measured in $B^+\to K^{*0}\pi^+$.

The assumption of equal and opposite p'_P and p'_V amplitudes lies behind a prediction by Lipkin [18] that one expects constructive interference between the nonstrange and strange components of the η, and destructive interference in the η', for the decays $B^+\to K^{*+}(\eta,\eta')$. This is valid if the penguin transition $\bar{b}\to\bar{s}$ leads to an intermediate $\bar{s}u$ final state accompanied by any number of gluons, as long as there is not some fundamental asymmetry in the wave function between the $\bar{s}$ and the u. If the final light $q\bar{q}$ pair is then produced in a flavor-SU(3) invariant manner, the p'_P and p'_V amplitudes will be equal and opposite. (Gluons must be present; otherwise one could rotate away any $\bar{b}\to\bar{s}$ transition by a redefinition of quark fields [20].)

The full generality of Lipkin's argument is less obvious. The transition $\bar{b}\to\bar{s}+$ (meson) has different Lorentz structure when the meson is a pseudoscalar (our p'_V amplitude) than when it is a vector (our p'_P amplitude). The p'_V and p'_P amplitudes indeed fail to be equal and opposite in several explicit calculations to be discussed in Sec. IV.

One might ask whether there is *any* evidence so far for amplitudes of the $a_P^{(\prime)}$ type. In Table III we collect a number of decay modes which can shed light on this question. We list the mode, the amplitude expected to dominate, and the

TABLE III. Some B decay modes capable of distinguishing between $a_P^{(\prime)}$-type and $a_V^{(\prime)}$-type amplitudes.

Decay mode	Dominant amplitude	Signal events	Expected background	$\mathcal{B}$ upper limit $\times10^{-6}$
$B^+\to\rho^+\pi^0$	t_P	8	5.5 ± 1.2	77
$\rho^0\pi^+$	t_V	4	2.3 ± 0.3	43
$\omega\pi^+$	t_V	8.8		[a]
$\phi\pi^+$	s_P	0		5.6
ρ^+K^0	p'_V	0	0	48
ρ^0K^+	p'_V	1	3.8 ± 0.2	19
ωK^+	p'_V	12		[a]
ϕK^+	p'_P	0		5.3
$K^{*0}\pi^+$	p'_P	2	1.0 ± 0.6	41
$K^{*+}\pi^0$	p'_P	4	1.9 ± 0.7	99
$B^0\to\rho^-\pi^+$	t_V	[b]	[b]	[c]
$\rho^+\pi^-$	t_P	[b]	[b]	[c]
$\phi\pi^0$	s_P	0		6.5
ρ^-K^+	p'_V	2	2.0 ± 0.4	35
ρ^0K^0	p'_V	0	0	39
ϕK^0	p'_P	2		42
$K^{*+}\pi^-$	p'_P	3	0.7 ± 0.2	72
$K^{*0}\pi^0$	p'_P	0	1.1 ± 0.3	28

[a]Signal observed (see text).
[b]Sum of channels has 7 events above expected background of 2.9 ±0.7.
[c]Upper limit on average branching ratio is 88×10^{-6}.

number of signal events, expected backgrounds, and upper limits on the branching ratios in units of 10^{-6} reported by CLEO II [14]. We do not list the coefficients of the dominant amplitudes, which may be found in Tables I and II.

None of the upper limits shown in Table III conflicts with the expectation that the t_V amplitude has already been seen in $B^+ \to \omega\pi^+$ and the p'_V amplitude has already been seen in $B^+ \to \omega K^+$. If these are the dominant amplitudes, one expects

$$\mathcal{B}(B^0 \to \rho^-\pi^+) = 2\mathcal{B}(B^+ \to \rho^0\pi^+) = 2\mathcal{B}(B^+ \to \omega\pi^+) \tag{12}$$

and

$$\begin{aligned}\mathcal{B}(B^+ \to \rho^+K^0) &= \mathcal{B}(B^0 \to \rho^-K^+) = 2\mathcal{B}(B^+ \to \rho^0K^+)\\ &= 2\mathcal{B}(B^0 \to \rho^0K^0) = 2\mathcal{B}(B^+ \to \omega K^+).\end{aligned} \tag{13}$$

The case of $B^0 \to \rho^\pm\pi^\mp$ is particularly interesting since the excess of signal over expected background is the largest of any in Table III, but the process requires flavor tagging in order to separate the t_V-dominated decay $B^0 \to \rho^-\pi^+$ from the t_P-dominated decay $B^0 \to \rho^+\pi^-$. Interesting statements about the relative magnitudes of amplitudes will require about a factor of 3 more data than those on which Table III was based.

E. Relations between $\Delta S = 0$ and $|\Delta S| = 1$ decays

Comparison of decay rates between $\Delta S = 0$ and $|\Delta S| = 1$ processes can help in determining ratios of magnitudes of CKM elements. For example, one expects

$$\frac{\mathcal{B}(B^+ \to K^{*0}\pi^+)}{\mathcal{B}(B^+ \to \overline{K^{*0}}K^+)} = \frac{\mathcal{B}(B^+ \to \rho^+K^0)}{\mathcal{B}(B^+ \to K^{*+}\overline{K^0})} = |V_{ts}/V_{td}|^2, \tag{14}$$

assuming that the top quark dominates the penguin amplitudes in these sets of processes. In certain ratios SU(3) breaking form factor effects cancel out. (See Ref. [13] for a more complete discussion.)

Once the dominant amplitudes (such as t_V and p'_V, for which we already have evidence) have been mapped out, one can use flavor SU(3) to anticipate the smaller amplitudes (like t'_V and p_V). Taking account of SU(3) breaking, we have

$$t'_V/t_V = t'_P/t_P = \lambda(f_K/f_\pi). \tag{15}$$

For penguin amplitudes in the flavor-SU(3) limit,

$$p_V/p'_V = p_P/p'_P = s_V/s'_V = s_P/s'_P = V_{td}/V_{ts} \tag{16}$$

(assuming top-quark dominance of the penguin amplitudes). One can then, in the manner of Ref. [12], search for processes in which two amplitudes with two different weak phases contribute with comparable strength. If these amplitudes have different strong phases as well, there is a possibility of a large CP asymmetry in comparing the rate for a process with its charge conjugate.

IV. PREDICTIONS OF SPECIFIC MODELS

Calculations of $B \to (PP, VP, VV)$ decay rates over the past ten years, involving assumptions about factorization and using specific B–to–light-meson form factors, include those of Refs. [5,21–27]. For the most part, these works have successfully anticipated those $B \to PP$ decays observed at a branching ratio level of 10^{-5} or greater, such as $B^0 \to K^+\pi^-$. The decay $B^0 \to \pi^+\pi^-$ is expected to correspond to a branching ratio not much below 10^{-5}.

A common feature of all the calculations is their expectation that $\mathcal{B}(B^+ \to \omega K^+)/\mathcal{B}(B^+ \to \phi K^+) \ll 1$, in disagreement with the CLEO results [1]. In our language, these calculations predict $|p'_V/p'_P| \ll 1$; in the work of Ref. [22], the contribution of p'_V is vanishingly small in certain decays. This is a result of the specifically chosen form factors used to calculate hadronic matrix elements of penguin operators.

The authors of Ref. [27] propose a new source of penguin terms, associated with charmed quarks in the loop rather than top quarks as is conventionally assumed (see also Ref. [28]). Their prediction of the $B^+ \to \omega K^+/\phi K^+$ ratio of rates nonetheless remains too small, with $\mathcal{B}(B^+ \to \omega K^+)/\mathcal{B}(B^+ \to \phi K^+) \approx 1/6$ to 0.6 in contradiction to experiment. This assumption implies weak phases of $\mathrm{Arg}(V^*_{cb}V_{cd}) = \pi$ and $\mathrm{Arg}(V^*_{cb}V_{cs}) = 0$ for $\Delta S = 0$ and $|\Delta S| = 1$ penguin amplitudes, respectively. If the top quark were dominant instead, one would have weak phases of $\mathrm{Arg}(V^*_{tb}V_{td}) = -\beta$ and $\mathrm{Arg}(V^*_{tb}V_{ts}) = \pi$. One cannot distinguish between a weak phase of π and one of zero in the $|\Delta S| = 1$ transitions, but it should be possible to tell the difference between the weak phase of zero and $-\beta$ for the $\Delta S = 0$ amplitudes. That distinction lies beyond the scope of the present work.

The relative signs of contributions from p'_P and p'_V in the model of Ref. [5] are such that one expects $\mathcal{B}(B \to K^*\eta) > \mathcal{B}(B \to K^*\eta')$ (see also Ref. [18]). For the corresponding decays with K replacing K^*, the prediction [5,18] is $\mathcal{B}(B \to K\eta) < \mathcal{B}(B \to K\eta')$, as observed for charged B's [17].

The authors of Ref. [5] do not include the s'_V terms, which may be important. For the corresponding PP decays, numerous authors [12,18,19] have noted that the singlet amplitude s' is required to understand the large $B \to K\eta'$ rate. There is some question as to the origin of this singlet amplitude. It most likely originates as a result of the gluonic anomaly in the axial U(1) current, but may be manifested in various ways, e.g., through an admixture of $c\bar{c}$ pairs or gluon pairs in the η' (and, to a lesser extent, η) wave function. The absence of a meaningful constraint on the strange-quark content of the η' (achievable by measuring the rate for $\phi \to \eta'\gamma$) [29] leaves some room for such admixtures. A direct coupling of singlet pseudoscalar mesons through penguin-type diagrams introduced in Ref. [9] is another possibility.

The models do seem to predict roughly the right magnitude for t_V, which we expect to dominate the observed decay $B^+ \to \omega\pi^+$. An expectation of Ref. [5] common to other models is that $|t_P| > |t_V|$. In that case, one should expect $\mathcal{B}(B^+ \to \rho^+\pi^0) > \mathcal{B}(B^+ \to \rho^0\pi^+)$ and $\mathcal{B}(B^0 \to \rho^+\pi^-) > \mathcal{B}(B^0 \to \rho^-\pi^+)$. As one sees in Table III, there is no evidence yet for or against this hierarchy.

We find that many of our Eqs. (2)–(4) are not satisfied by

TABLE IV. Branching ratios for penguin-dominated B decays in two models, in units of 10^{-6}.

Decay	Chau *et al.*	Ciuchini *et al.*
$B^+ \to \rho^0 K^+$	0.6	3.9
$B^+ \to \omega K^+$	1.4	6.0
$B^+ \to K^{*0}\pi^+$	8.8	9.2
$B^+ \to \phi K^+$	14	15

the models of Chau *et al.* [5] and Ciuchini *et al.* [27]. The sources of the violations are of some interest.

In Ref. [5], the annihilation amplitude seems to have a large effect. We have noted that the ϕK^+ and ϕK^0 amplitudes should be equal by isospin when we neglect annihilation. Chau *et al.* find (including annihilation) that the branching ratios of these processes are 14×10^{-6} and 9×10^{-6}, respectively. This means that the ratio of the annihilation amplitude to p'_P must be at least 0.25 (which is surprisingly large) *if* p'_P and annihilation interfere constructively in ϕK^+. Otherwise, annihilation is even larger. Note that in the calculation of Ref. [5] (as in the others) p'_P (rather than p'_V) is the dominant amplitude in $|\Delta S|=1$ decays. Thus, the effects of annihilation in other processes (dominated by the smaller p'_V) are even larger. For instance, these authors find $\mathcal{B}(B^+\to\rho^+K^0)=0.34\times 10^{-6}$ and $2\mathcal{B}(B^0\to\rho^0K^0)=0.70\times 10^{-6}$, while these numbers should be approximately equal by our Eq. (2) if c'_P is negligible.

In the calculation by Ciuchini *et al.* the last two rates come out to be quite different as a result of a significant electroweak penguin contribution to the c'_P amplitude. The authors find $\mathcal{B}(B^+\to\rho^+K^0)=27\times 10^{-6}$ and $2\mathcal{B}(B^0\to\rho^0K^0)=8.8\times 10^{-6}$. The enhancement relative to the results of Ref. [5] comes from the ''charming penguin'' terms. This illustrates the large spread of model predictions.

In Table IV we compare some other results from Ref. [5] (see also Ref. [26]) and Ref. [27], where again rates are enhanced by ''charming penguins.'' The first authors neglected s'_P. In our treatment, the branching ratios for the processes in the first and second rows should be approximately equal, and so should those for the processes in the third and fourth rows. The differences in Ciuchini *et al.* show the effect of s'_P and involve some nonet-symmetry and SU(3) breaking effects. The combined effect, resulting in amplitude differences at a level of 25–30%, is not unexpected. On the other hand, the rate difference between the first two processes in Chau *et al.*, arising from nonet-symmetry breaking alone, seems quite large for such effects.

V. CONCLUSIONS

The decays $B^+\to\omega\pi^+$ (still requiring confirmation) and ωK^+ seen at branching ratio levels of about 10^{-5} by the CLEO Collaboration [1] can be used, with the help of flavor SU(3), to anticipate the observability of other charmless $B\to VP$ decays in the near future. We have indicated which amplitudes in the flavor-SU(3) decomposition are likely to be large as a result of present evidence. These consist of a strangeness-preserving ''tree'' amplitude t_V and a strangeness-changing penguin amplitude p'_V. In both cases the subscript indicates that the spectator quark is incorporated into a vector (V) meson.

Other decays depending on the amplitude t_V are $B^+\to\rho^0\pi^+$ and $B^0\to\rho^-\pi^+$. If t_V is the dominant amplitude in these processes, we expect $\Gamma(B^+\to\rho^0\pi^+)=\Gamma(B^+\to\omega\pi^+)$ and $\Gamma(B^0\to\rho^-\pi^+)=2\Gamma(B^+\to\omega\pi^+)$. Furthermore, model calculations predicting $|t_P|>|t_V|$ imply that decays expected to be dominated by t_P, such as $B^+\to\rho^+\pi^0$ and $B^0\to\rho^+\pi^-$, will also have branching ratios in excess of 10^{-5}.

An appreciable value for the amplitude p'_V, somewhat of a surprise in conventional models, implies that $B\to\rho K$ decays should be observable at branching ratio levels in excess of 10^{-5}. The smallness of the ratio $\mathcal{B}(B^+\to\phi K^+)/\mathcal{B}(B^+\to\omega K^+)$ indicates that $|p'_P|<|p'_V|$. The amplitude p'_P should dominate not only $B\to\phi K$ but also $B\to K^*\pi$ decays. Evidence for any of these would then tell us the magnitude of p'_P. The relative phase of p'_P and p'_V is probed by $B\to K^*(\eta,\eta')$ decays.

We have argued that singlet amplitudes s,s', corresponding to disconnected quark diagrams, are more likely to be appreciable when pseudoscalar mesons η,η' are disconnected from the rest of the diagram than when vector mesons ω,ϕ are disconnected. Thus, we expect $|s'_V|>|s'_P|$ and $|s_V|>|s_P|$. (Recall that the subscript refers to the meson in which the *spectator* quark is incorporated.) We have suggested several tests for non-zero singlet amplitudes, including a number of triangle and rate relations, and have outlined a program for determining the magnitude and phase of s'_V.

Once the dominant t, p', and s'_V amplitudes have been determined, flavor SU(3) predicts the amplitudes t', p, and s_V. One can then (cf. Ref. [12]) determine which processes are likely to exhibit noticeable interferences between two or more amplitudes, thereby having the potential for displaying direct CP-violating asymmetries.

The CLEO Collaboration [1] has also reported the observation of the decay $B\to\phi K^*$, with a branching ratio of $(1.3^{+0.7}_{-0.6}\pm 0.2)\times 10^{-5}$ when charged and neutral modes are combined. (Isospin invariance implies equal rates for the two.) Decays of the form $B\to VV$ are more complicated than $B\to PP$ or $B\to VP$ decays because of the three possible partial waves in the final state. Once these are separated out, for example using decay angular distributions [30], an analysis similar to the one presented here becomes possible for $B\to VV$ decays as well.

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