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Hadronic B decays to charmless VT final states

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Abstract. Charmless hadronic decays of B mesons to a vector meson (V) and a tensor meson (T) are analyzed in the frameworks of both flavor SU(3) symmetry and generalized factorization. We also make comments on B decays to two tensor mesons in the final states. Certain ways to test the validity of the generalized factorization are proposed, using $B \to VT$ decays. We calculate the branching ratios and CP asymmetries using the *full* effective Hamiltonian including all the *penguin* operators and the form factors obtained in the non-relativistic quark model of Isgur, Scora, Grinstein and Wise.

1 Introduction

In the next few years B factories operating at KEK and SLAC will provide plenty of new experimental data on B decays. It is expected that an improved new bound will be put on the branching ratios for various decay modes and many decay modes with small branching ratios will be observed for the first time. Thus more information on rare decays of B mesons will be available soon. Experimentally several tensor mesons have been observed [1], such as the isovector $a_2(1320)$, the isoscalars $f_2(1270)$, $f_2'(1525)$, $f_2(2010)$, $f_2(2300)$, $f_2(2340)$, $\chi_{c2}(1P)$, $\chi_{b2}(1P)$ and $\chi_{c2}(2P)$, and the isospinors $K_2^*(1430)$ and $D_2^*(2460)$. Experimental data on the branching ratios for B decays involving a vector (V) and a tensor meson (T) in the final state provide only upper bounds, as follows [1]:

$$\begin{aligned}
\mathcal{B}(B^+ \to \rho^+ D_2^*(2460)^0) &< 4.7 \times 10^{-3}, \\
\mathcal{B}(B^0 \to \rho^+ D_2^*(2460)^-) &< 4.9 \times 10^{-3}, \\
\mathcal{B}(B^+ \to \rho^0 K_2^*(1430)^+) &< 1.5 \times 10^{-3}, \\
\mathcal{B}(B^0 \to \rho^0 K_2^*(1430)^0) &< 1.1 \times 10^{-3}, \\
\mathcal{B}(B^+ \to \phi K_2^*(1430)^+) &< 3.4 \times 10^{-3}, \\
\mathcal{B}(B^0 \to \phi K_2^*(1430)^0) &< 1.4 \times 10^{-3}, \\
\mathcal{B}(B^+ \to \rho^0 a_2(1320)^+) &< 7.2 \times 10^{-4}. \qquad (1)
\end{aligned}$$

In particular, the process $B \to K_2^* \gamma$ has been observed for the first time by the CLEO Collaboration with a branching ratio of $(1.66^{+0.59}_{-0.53} \pm 0.13) \times 10^{-5}$ [2].

There have been a few works [3–5] studying two-body B decays involving a tensor meson T ($J^P = 2^+$) in the final state using the non-relativistic quark model of Isgur, Scora, Grinstein and Wise (ISGW) [6] in the framework of factorization. Those works considered only the tree diagram contribution. However, in the charmless $|\Delta S| = 1$ decays, the *penguin* diagram contribution is enhanced by the CKM matrix elements $V_{tb}^* V_{ts}$ and becomes dominant.

In a recent work [7], we have studied B decays to a pseudoscalar meson and a tensor meson. In this work, the previous analysis is extended to charmless hadronic decays of B mesons to a vector meson and a tensor meson in the frameworks of *both* flavor SU(3) symmetry and the generalized factorization. We also comment on B decays to *two* tensor mesons in the final states. First, a model-independent analysis in $B \to VT$ decays is presented, purely based on the flavor SU(3) symmetry. Then we calculate branching ratios and CP asymmetries for both $|\Delta S| = 1$ and $\Delta S = 0$ decays, using the *full* effective Hamiltonian including all the penguin operators, and the ISGW quark model to obtain relevant form factors. In order to bridge the flavor SU(3) approach and the factorization approach, we present a set of relations between a flavor SU(3) amplitude and a corresponding amplitude in the factorization in $B \to VT$ decays. Emphasizing the interplay between both schemes, we propose certain ways to test the validity of both approaches in future experiment.

This work is organized as follows. In Sect. 2 we discuss our frameworks and make some comments on $B \to TT$ decays. In Sect. 3 we present a model-independent analysis of $B \to VT$ decays based on SU(3) symmetry. In Sect. 4 the two-body decays $B \to VT$ are analyzed in the framework of generalized factorization. The branching ratios and CP asymmetries are calculated using the form factors obtained in the ISGW quark model. Finally, in Sect. 5 we conclude our analysis.

2 Framework

In this analysis of $B \to VT$ decays, we use the same frameworks, such as the flavor SU(3) approach and the general-

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ized factorization scheme, and the same notation as those used in our previous analysis of $B \to PT$ decays [7]. Thus, we refer to [7] for the notation used in our frameworks.

Since in $B \to VT$ decays there are three possible partial waves with $l = 1, 2, 3$ in the final state, $B \to VT$ processes are more complicated than $B \to PT$ processes. For the SU(3) analysis of $B \to VT$ decays, these partial waves in the final state need to be separated out. We will assume that this can be done by certain methods such as the one using angular distributions in $B \to VV$ decays [8].

We use the following phase convention for the vector and the tensor mesons:

$$\begin{aligned}
\rho^+(a_2^+) &= u\bar{d}, \quad \rho^0(a_2^0) = -\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \\
\rho^-(a_2^-) &= -\bar{u}d, \\
K^{*+}(K_2^{*+}) &= u\bar{s}, \quad K^{*0}(K_2^{*0}) = d\bar{s}, \quad \bar{K}^{*0}(\bar{K}_2^{*0}) = \bar{d}s, \\
K^{*-}(K_2^{*-}) &= -\bar{u}s, \\
\omega &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad \phi = s\bar{s}, \\
f_2 &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\phi_T + (s\bar{s})\sin\phi_T, \\
f_2' &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\phi_T - (s\bar{s})\cos\phi_T, \qquad (2)
\end{aligned}$$

where the mixing angle ϕ_T is given by $\phi_T = \arctan(1/(2^{1/2})) - 28^0 \approx 7^\circ$ [3,9].

In the ISGW quark model, the hadronic matrix elements for $B \to VT$ decays are parameterized as [6]:

$$\langle 0|V^\mu|V\rangle = f_V m_V \epsilon^\mu, \qquad (3)$$

$$\begin{aligned}
\langle T|j^\mu|B\rangle &= \mathrm{i}h(m_P^2)\epsilon^{\mu\nu\rho\sigma}\epsilon^*_{\nu\alpha}p_B^\alpha(p_B + p_T)_\rho(p_B - p_T)_\sigma \\
&+ k(m_P^2)\epsilon^{*\mu\nu}(p_B)_\nu \\
&+ \epsilon^*_{\alpha\beta}p_B^\alpha p_B^\beta\Big[b_+(m_P^2)(p_B + p_T)^\mu \\
&+ b_-(m_P^2)(p_B - p_T)^\mu\Big], \qquad (4)
\end{aligned}$$

where $j^\mu = V^\mu - A^\mu$. V^μ and A^μ denote a vector and an axial-vector current, respectively. f_P denotes the decay constant of the relevant pseudoscalar meson. $h(m_P^2)$, $k(m_P^2)$, $b_+(m_P^2)$, and $b_-(m_P^2)$ express the form factors for the $B \to T$ transition, $F^{B\to T}(m_P^2)$, which have been calculated at $q^2 = m_P^2$ ($q^\mu \equiv p_B^\mu - p_T^\mu$) in the ISGW quark model [6]. p_B and p_T denote the momentum of the B meson and the tensor meson, respectively. We note that the matrix element

$$\langle 0|j^\mu|T\rangle = 0, \qquad (5)$$

because the trace of the polarization tensor $\epsilon^{\mu\nu}$ of the tensor meson T vanishes and the auxiliary condition holds, $p_T^\mu\epsilon_{\mu\nu} = 0$ [10]. Therefore, in the generalized factorization scheme, just as in the case of $B \to PT$ decays, the decay amplitudes for $B \to VT$ can be considerably simplified, compared to those for other two-body charmless decays of B mesons such as $B \to PP$, PV, and VV: Any decay amplitude for $B \to VT$ is simply proportional to the decay constant f_V and a certain linear combination of the form factors $F^{B\to T}$, i.e., there is no such amplitude proportional to $f_T \times$ (form factor for$B \to V$).

We would like to make comments on decays of B mesons to two tensor mesons in the final state. Since $\langle 0|j_\mu|T\rangle = 0$, in the factorization scheme the decay amplitude for $B \to TT$ decays always vanishes:

$$\langle TT|H_{\mathrm{eff}}|B\rangle \sim \langle T|j^\mu|B\rangle\langle 0|j_\mu|T\rangle = 0. \qquad (6)$$

A non-zero rate for any $B \to TT$ decay would arise from non-factorizable effects or final state interactions. Therefore, search for any $B \to TT$ modes in future experiments can provide a critical test of the factorization ansatz.

3 Flavor SU(3) analysis of $B \to VT$ decays

The coefficients of the SU(3) amplitudes in $B \to VT$ are listed in Tables 1 and 2 for strangeness-conserving ($\Delta S = 0$) and strangeness-changing ($|\Delta S| = 1$) processes, respectively. For the notation of the SU(3) amplitudes, we refer to [7].

Note that the contributions of the SU(3) amplitudes with the subscript V vanish in the framework of factorization, because those contributions contain the matrix element $\langle T|J_\mu^{\mathrm{weak}}|0\rangle$ which is zero, see (5). We will present some ways to test the validity of both the SU(3) approach and the factorization scheme in future experiments.

Among the $\Delta S = 0$ amplitudes, the tree diagram contribution is expected to be largest so that from Table 1 the decays $B^+ \to \rho^+ a_2^0$, $\rho^+ f_2$, and $B^0 \to \rho^+ a_2^-$ are expected to have the largest rates. Here we have noticed that in $B^+ \to \rho^+ f_2^{(\prime)}$ decays, $\cos\phi_T = 0.99$ and $\sin\phi_T = 0.13$, since the mixing angle $\phi_T \approx 7^\circ$. The amplitudes for the processes $B \to \phi f_2^{(\prime)}$, ϕa_2, and $K^* K_2^*$ have only penguin diagram contributions, so they are expected to be small. In principle, the penguin contribution (combined with the smaller color-suppressed EW penguin) $p_T \equiv P_T - (1/3)P_{\mathrm{EW},T}$ can be measured in $B^{+(0)} \to \bar{K}^{*0} K_2^{*+(0)}$. The tree contribution (combined with much smaller color-suppressed EW penguin) $t_T \equiv T_T + P^C_{\mathrm{EW},T}$ are measured by the combination $A(B^{+(0)} \to \bar{K}^{*0} K_2^{*+(0)}) - A(B^0 \to \rho^+ a_2^-)$. The amplitudes for $B^0 \to \rho^0 f_2'$ and $\omega f_2'$ have the color-suppressed tree contributions, $C_T(C_V)$, but are suppressed by $\sin\phi_T$ so that they are expected to be small. We shall see that these expectations based on the SU(3) approach are consistent with those calculated in the factorization approximation. However, there exist some cases in which the predictions based on both approaches are inconsistent. Note that in Table 1 the amplitudes for $B^0 \to \rho^- a_2^+$ and $B^{+(0)} \to K^{*+(0)} \bar{K}_2^{*0}$ can be decomposed into linear combinations of the SU(3) amplitudes as follows:

$$A(B^0 \to \rho^- a_2^+) = -T_V - P_V - (2/3)P^C_{\mathrm{EW},V}, \qquad (7)$$

$$\begin{aligned}
A(B^+ \to K^{*+}\bar{K}_2^{*0}) &= A(B^0 \to K^{*0}\bar{K}_2^{*0}) \\
&= P_V - (1/3)P^C_{\mathrm{EW},V}. \qquad (8)
\end{aligned}$$

Table 1. Coefficients of SU(3) amplitudes in $B \to VT$ ($\Delta S = 0$). The coefficients of the SU(3) amplitudes with the subscript V are expressed in square brackets. As explained in Sect. 2, the contributions of the SU(3) amplitudes with the subscript V vanish in the framework of factorization, because those contributions contain the matrix element $\langle T|J_\mu^{\mathrm{weak}}|0\rangle$, which is zero. Here c and s denote $\cos\phi_T$ and $\sin\phi_T$, respectively

$B \to VT$	factor	$T_T[T_V]$	$C_T[C_V]$	$S_T[S_V]$	$P_T[P_V]$	$P_{\mathrm{EW},T}$ $[P_{\mathrm{EW},V}]$	$P^C_{\mathrm{EW},T}[P^C_{\mathrm{EW},V}]$
$B^+ \to \rho^+ a_2^0$	$-\frac{1}{\sqrt{2}}$	1	[1]	0	1, [−1]	[1]	$\frac{2}{3}$, $\left[\frac{1}{3}\right]$
$B^+ \to \rho^+ f_2$	$\frac{1}{\sqrt{2}}$	c	$[c]$	$[2c+\sqrt{2}s]$	c, $[c]$	$\left[\frac{c-\sqrt{2}s}{3}\right]$	$\frac{2c}{3}$, $\left[-\frac{c}{3}\right]$
$B^+ \to \rho^+ f_2'$	$\frac{1}{\sqrt{2}}$	s	$[s]$	$[2s-\sqrt{2}c]$	s, $[s]$	$\left[\frac{\sqrt{2}c+s}{3}\right]$	$\frac{2s}{3}$, $\left[-\frac{s}{3}\right]$
$B^+ \to \rho^0 a_2^+$	$-\frac{1}{\sqrt{2}}$	[1]	1	0	−1, [1]	1	$\frac{1}{3}$, $\left[\frac{2}{3}\right]$
$B^+ \to \omega a_2^+$	$\frac{1}{\sqrt{2}}$	[1]	1	2	1, [1]	$\frac{1}{3}$	$-\frac{1}{3}$, $\left[\frac{2}{3}\right]$
$B^+ \to \phi a_2^+$	1	0	0	1	0	$-\frac{1}{3}$	0
$B^+ \to K^{*+} \bar{K}_2^{*0}$	1	0	0	0	[1]	0	$\left[-\frac{1}{3}\right]$
$B^+ \to \bar{K}^{*0} K_2^{*+}$	1	0	0	0	1	0	$-\frac{1}{3}$
$B^0 \to \rho^+ a_2^-$	−1	1	0	0	1	0	$\frac{2}{3}$
$B^0 \to \rho^- a_2^+$	−1	[1]	0	0	[1]	0	$\left[\frac{2}{3}\right]$
$B^0 \to \rho^0 a_2^0$	$-\frac{1}{2}$	0	1, [1]	0	−1, [−1]	1, [1]	$\frac{1}{3}$, $\left[\frac{1}{3}\right]$
$B^0 \to \rho^0 f_2$	$-\frac{1}{2}$	0	c, $[-c]$	$[-(2c+\sqrt{2}s)]$	$-c$, $[-c]$	c, $\left[\frac{-c+\sqrt{2}s}{3}\right]$	$\frac{c}{3}$, $\left[\frac{c}{3}\right]$
$B^0 \to \rho^0 f_2'$	$-\frac{1}{2}$	0	s, $[-s]$	$[-(2s-\sqrt{2}c)]$	$-s$, $[-s]$	s, $\left[-\frac{(\sqrt{2}c+s)}{3}\right]$	$\frac{s}{3}$, $\left[\frac{s}{3}\right]$
$B^0 \to \omega a_2^0$	$\frac{1}{2}$	0	1, [−1]	2	1, [1]	$\frac{1}{3}$, [−1]	$-\frac{1}{3}$, $\left[-\frac{1}{3}\right]$
$B^0 \to \omega f_2$	$\frac{1}{2}$	0	c, $[c]$	$2c$, $[(2c+\sqrt{2}s)]$	c, $[c]$	$\frac{c}{3}$, $\left[\frac{c-\sqrt{2}s}{3}\right]$	$-\frac{c}{3}$, $\left[-\frac{c}{3}\right]$
$B^0 \to \omega f_2'$	$\frac{1}{2}$	0	s, $[s]$	$2s$, $[(2s-\sqrt{2}c)]$	s, $[s]$	$\frac{s}{3}$, $\left[\frac{s+\sqrt{2}c}{3}\right]$	$-\frac{s}{3}$, $\left[-\frac{s}{3}\right]$
$B^0 \to \phi a_2^0$	$\frac{1}{\sqrt{2}}$	0	0	1	0	$-\frac{1}{3}$	0
$B^0 \to \phi f_2$	$\frac{1}{\sqrt{2}}$	0	0	c	0	$-\frac{c}{3}$	0
$B^0 \to \phi f_2'$	$\frac{1}{\sqrt{2}}$	0	0	s	0	$-\frac{s}{3}$	0
$B^0 \to K^{*0} \bar{K}_2^{*0}$	1	0	0	0	[1]	0	$\left[-\frac{1}{3}\right]$
$B^0 \to \bar{K}^{*0} K_2^{*0}$	1	0	0	0	1	0	$-\frac{1}{3}$

Table 2. Coefficients of SU(3) amplitudes in $B \to VT$ ($|\Delta S| = 1$)

$B \to VT$	factor	$T'_T[T'_P]$	$C'_T[C'_V]$	$S'_T[S'_V]$	$P'_T[P'_V]$	$P'_{\mathrm{EW},T}$ $[P'_{\mathrm{EW},V}]$	$P^{C\prime}_{\mathrm{EW},T}[P^{C\prime}_{\mathrm{EW},V}]$
$B^+ \to K^{*+} a_2^0$	$-\frac{1}{\sqrt{2}}$	1	[1]	0	1	[1]	$\frac{2}{3}$
$B^+ \to K^{*+} f_2$	$\frac{1}{\sqrt{2}}$	c	$[c]$	$[2c+\sqrt{2}s]$	c, $[\sqrt{2}s]$	$\left[\frac{c-\sqrt{2}s}{3}\right]$	$\frac{2}{3}c$, $\left[-\frac{\sqrt{2}s}{3}\right]$
$B^+ \to K^{*+} f_2'$	$\frac{1}{\sqrt{2}}$	s	$[s]$	$[2s-\sqrt{2}c]$	s, $[-\sqrt{2}c]$	$\left[\frac{s+\sqrt{2}c}{3}\right]$	$\frac{2}{3}s$, $\left[\frac{\sqrt{2}c}{3}\right]$
$B^+ \to K^{*0} a_2^+$	1	0	0	0	1	0	$-\frac{1}{3}$
$B^+ \to \rho^+ K_2^{*0}$	1	0	0	0	[1]	0	$\left[-\frac{1}{3}\right]$
$B^+ \to \rho^0 K_2^{*+}$	$-\frac{1}{\sqrt{2}}$	[1]	1	0	[1]	1	$\left[\frac{2}{3}\right]$
$B^+ \to \omega K_2^{*+}$	$\frac{1}{\sqrt{2}}$	[1]	1	2	[1]	$\frac{1}{3}$	$\left[\frac{2}{3}\right]$
$B^+ \to \phi K_2^{*+}$	1	0	0	1	1	$-\frac{1}{3}$	$-\frac{1}{3}$
$B^0 \to K^{*+} a_2^-$	−1	1	0	0	1	0	$\frac{2}{3}$
$B^0 \to K^{*0} a_2^0$	$\frac{1}{\sqrt{2}}$	0	[−1]	0	1	[−1]	$-\frac{1}{3}$
$B^0 \to K^{*0} f_2$	$\frac{1}{\sqrt{2}}$	0	$[c]$	$[2c+\sqrt{2}s]$	c, $[\sqrt{2}s]$	$\left[\frac{c-\sqrt{2}s}{3}\right]$	$-\frac{c}{3}$, $\left[-\frac{\sqrt{2}s}{3}\right]$
$B^0 \to K^{*0} f_2'$	$\frac{1}{\sqrt{2}}$	0	$[s]$	$[2s-\sqrt{2}c]$	s, $[-\sqrt{2}c]$	$\left[\frac{s+\sqrt{2}c}{3}\right]$	$-\frac{s}{3}$, $\left[\frac{\sqrt{2}c}{3}\right]$
$B^0 \to \rho^- K_2^{*+}$	−1	[1]	0	0	[1]	0	$\left[\frac{2}{3}\right]$
$B^0 \to \rho^0 K_2^{*0}$	$-\frac{1}{\sqrt{2}}$	0	1	0	[−1]	1	$\left[\frac{1}{3}\right]$
$B^0 \to \omega K_2^{*0}$	$\frac{1}{\sqrt{2}}$	0	1	2	[1]	$\frac{1}{3}$	$\left[-\frac{1}{3}\right]$
$B^0 \to \phi K_2^{*0}$	1	0	0	1	1	$-\frac{1}{3}$	$-\frac{1}{3}$

As previously explained, in factorization the rates for these processes vanish because all the SU(3) amplitudes carry the subscript V. Non-zero decay rates for these processes would arise from non-factorizable effects or final state interactions. Thus, in principle one can test the validity of the factorization ansatz by measuring the rates for these decays in future experiments. Furthermore, the non-factorizable penguin contribution, if it exists (combined with the smaller color-suppressed EW penguin) $p_V \equiv P_V - (1/3)P_{\mathrm{EW},V}$ can be measured in $B^{+(0)} \to \bar{K}^{*+(0)} \bar{K}_2^{*+(0)}$. Also, supposing that P_V is very small compared to T_V as usual, one can determine the magnitude of T_V by measuring the rate for $B^0 \to \rho^- a_2^+$.

In the $|\Delta S| = 1$ decays, the (strong) penguin contribution P' is expected to dominate because of enhancement by the ratio of the CKM elements $|V_{tb}^* V_{ts}|/|V_{ub}^* V_{us}| \approx 50$. We note that the amplitudes for $B^+ \to K^{*0} a_2^+$ and $B^+ \to \rho^+ K_2^{*0}$ have only penguin contributions, respectively:

$$A(B^+ \to K^{*0} a_2^+) = P'_T - \frac{1}{3} P_{\mathrm{EW},T}^{C\prime}, \tag{9}$$

$$A(B^+ \to \rho^+ K_2^{*0}) = P'_V - \frac{1}{3} P_{\mathrm{EW},V}^{C\prime}. \tag{10}$$

Thus the penguin contribution (combined with the smaller color-suppressed EW penguin) $p'_T \equiv P'_T - (1/3)P_{\mathrm{EW},T}^{C\prime}$ is measured in $B^+ \to K^{*0} a_2^+$. Similarly, $p'_V \equiv P'_V - (1/3)P_{\mathrm{EW},V}^{C\prime}$ is determined in $B^+ \to \rho^+ K_2^{*0}$. (In fact, $p'_V = 0$ in factorization.) By comparing the branching ratios for these two modes measured in experiment, one can determine which contribution (i.e., p'_T or p'_V) is larger. The (additional penguin) SU(3) singlet amplitude S' is expected to be very small because of the Okubo–Zweig–Iizuka (OZI) suppression. As in $\Delta S = 0$ decays, there are certain processes whose amplitudes can be expressed by the SU(3) amplitudes, but are expected to vanish in factorization: For instance, $A(B^+ \to \rho^+ K_2^{*0})$ is given by (10) and $A(B^0 \to \rho^- K_2^{*+}) = -\left(T'_V + P'_V + (2/3)P_{\mathrm{EW},V}^{C\prime}\right)$. Thus, in principle measurement of the rates for these decays can be used to test the factorization ansatz. We also note that the decay amplitudes for modes $B^+ \to \rho^0 K_2^{*+}$ and $B^0 \to \rho^0 K_2^{*0}$ can be respectively written as

$$\begin{aligned} &A(B^+ \to \rho^0 K_2^{*+}) \\ &\quad = -\frac{1}{\sqrt{2}} \left(T'_V + C'_T + P'_V + P'_{\mathrm{EW},T} + \frac{2}{3} P_{\mathrm{EW},V}^{C\prime} \right), \\ &A(B^0 \to \rho^0 K_2^{*0}) \\ &\quad = -\frac{1}{\sqrt{2}} \left(C'_T - P'_V + P'_{\mathrm{EW},T} + \frac{1}{3} P_{\mathrm{EW},V}^{C\prime} \right). \end{aligned} \tag{11, 12}$$

Since in factorization only the amplitudes having the subscript T do not vanish, we shall see that $\mathcal{B}(B^+ \to \rho^0 K_2^{*+}) = \mathcal{B}(B^0 \to \rho^0 K_2^{*0})$ in the factorization scheme, where $\mathcal{B}$ denotes the branching ratio. Thus, if T'_V or P'_V is (not zero and) not very suppressed compared to C'_T, then there would be a sizable discrepancy in the relation $\mathcal{B}(B^+ \to \rho^0 K_2^{*+}) = \mathcal{B}(B^0 \to \rho^0 K_2^{*0})$, and in principle this can be tested in experiment.

From Tables 1 and 2, we find some useful relations among the decay amplitudes. The equivalence relations are for the $\Delta S = 0$ modes

$$\begin{aligned} &\frac{1}{\sqrt{2}} A(B^+ \to \phi a_2^+) = A(B^0 \to \phi a_2^0) \\ &\quad = \frac{1}{c} A(B^0 \to \phi f_2) = \frac{1}{s} A(B^0 \to \phi f'_2), \\ &A(B^+ \to K^{*+} \bar{K}_2^{*0}) = A(B^0 \to K^{*0} \bar{K}_2^{*0}), \\ &A(B^+ \to \bar{K}^{*0} K_2^{*+}) = A(B^0 \to \bar{K}^{*0} K_2^{*0}), \end{aligned} \tag{13}$$

and for the $|\Delta S| = 1$ modes

$$A(B^+ \to \phi K_2^{*+}) = A(B^0 \to \phi K_2^{*0}). \tag{14}$$

The quadrangle relations are for the $\Delta S = 0$ processes

$$\begin{aligned} &\frac{1}{c} A(B^+ \to \rho^+ f_2) - \frac{1}{s} A(B^+ \to \rho^+ f'_2) \\ &\quad = \sqrt{2} \left[\frac{1}{c} A(B^0 \to \rho^0 f_2) - \frac{1}{s} A(B^0 \to \rho^0 f'_2) \right] \\ &\quad = \sqrt{2} \left[\frac{1}{c} A(B^0 \to \omega f_2) - \frac{1}{s} A(B^0 \to \omega f'_2) \right], \end{aligned} \tag{15}$$

and for the $|\Delta S| = 1$ processes

$$\begin{aligned} &A(B^+ \to K^{*0} a_2^+) + \sqrt{2} A(B^+ \to K^{*+} a_2^0) \\ &\quad = \sqrt{2} A(B^0 \to K^{*0} a_2^0) + A(B^0 \to K^{*+} a_2^-), \\ &\frac{1}{c} A(B^+ \to K^{*+} f_2) - \frac{1}{s} A(B^+ \to K^{*+} f'_2) \\ &\quad = \frac{1}{c} A(B^0 \to K^{*0} f_2) - \frac{1}{s} A(B^0 \to K^{*0} f'_2), \\ &A(B^+ \to \rho^+ K^{*0}) + \sqrt{2} A(B^+ \to \rho^0 K^{*+}) \\ &\quad = A(B^0 \to \rho^- K^{*+}) + \sqrt{2} A(B^0 \to \rho^0 K_2^{*0}), \end{aligned} \tag{16}$$

where $c \equiv \cos\phi_T$ and $s \equiv \sin\phi_T$. Note that the above relations are derived purely based on flavor SU(3) symmetry. In the factorization scheme (neglecting the SU(3) amplitudes with the subscript V) we would have in addition the approximate relations as follows[1]. The following factorization relation would hold:

$$\sqrt{2} A(B^+ \to \rho^+ a_2^0) \approx A(B^0 \to \rho^+ a_2^-). \tag{17}$$

The quadrangle relations given in (15) and (16) would be divided into the following factorization relations: for the $\Delta S = 0$ processes

$$\begin{aligned} &\frac{1}{c} A(B^+ \to \rho^+ f_2) \approx \frac{1}{s} A(B^+ \to \rho^+ f'_2), \\ &\frac{1}{c} A(B^0 \to \rho^0 f_2) \approx \frac{1}{s} A(B^0 \to \rho^0 f'_2), \\ &\frac{1}{c} A(B^0 \to \omega f_2) \approx \frac{1}{s} A(B^0 \to \omega f'_2), \end{aligned} \tag{18}$$

[1] Considering SU(3) breaking effects, we use the symbol $\approx$ in the following relations instead of the equivalence symbol $=$

and for the $|\Delta S| = 1$ processes

$$\begin{aligned}
\sqrt{2}A(B^+ \to K^{*+}a_2^0) &\approx A(B^0 \to K^{*+}a_2^-), \\
A(B^+ \to K^{*0}a_2^+) &\approx \sqrt{2}A(B^0 \to K^{*0}a_2^0), \\
\frac{1}{c}A(B^+ \to K^{*+}f_2) &\approx \frac{1}{s}A(B^+ \to K^{*+}f_2'), \\
\frac{1}{c}A(B^0 \to K^{*0}f_2) &\approx \frac{1}{s}A(B^0 \to K^{*0}f_2'), \\
A(B^+ \to \rho^0 K_2^{*+}) &\approx A(B^0 \to \rho^0 K_2^{*0}), \\
A(B^+ \to \omega K_2^{*+}) &\approx A(B^0 \to \omega K_2^{*0}). \qquad (19)
\end{aligned}$$

Therefore, in principle the above relations given in (17), (18) and (19) provide an interesting way to test the factorization scheme by measuring and comparing magnitudes of the decay amplitudes involved in the relations. In a consideration of SU(3) breaking effects, the relation in (17) is best to use, because in fact this relation arises from isospin symmetry assuming $C_V = P_V = P_{\mathrm{EW},V} = P^C_{\mathrm{EW},V} = 0$. (However, if C_V is negligibly small (though not zero) compared to T_T, (17) will approximately hold.)

4 Analysis of $B \to VT$ using the Isgur–Scora–Grinstein–Wise model

The unpolarized decay rate for $B \to VT$ is given by

$$\begin{aligned}
\Gamma(B \to VT) = &\frac{G_F^2}{48\pi m_T^4} m_V f_V^2 \\
&\times |\{V_{ub}^* V_{ud(s)} \cdot (a_1 \text{ or } a_2) - V_{tb}^* V_{td(s)} \cdot (a_i{}'\mathrm{s})\}|^2 \\
&\cdot [\mathcal{X}|\boldsymbol{p}_V|^7 + \mathcal{Y}|\boldsymbol{p}_V|^5 + \mathcal{Z}|\boldsymbol{p}_V|^3], \qquad (20)
\end{aligned}$$

where $|\boldsymbol{p}_V|$ is the magnitude of the three-momentum of the final state particle V or T ($|\boldsymbol{p}_V| = |\boldsymbol{p}_T|$) in the rest frame of the B meson. The effective coefficients a_i are defined as $a_i = c_i^{\mathrm{eff}} + \xi c_{i+1}^{\mathrm{eff}}$ (i = odd) and $a_i = c_i^{\mathrm{eff}} + \xi c_{i-1}^{\mathrm{eff}}$ (i = even) with the effective WC's c_i^{eff} at the scale m_b [11,12], and by treating $\xi \equiv 1/N_c$ (N_c denotes the effective number of color) as an adjustable parameter. The factors $\mathcal{X}$, $\mathcal{Y}$, and $\mathcal{Z}$, respectively, are given by

$$\begin{aligned}
\mathcal{X} &= 8m_B^4 b_+^2, \\
\mathcal{Y} &= 2m_B^2 \left[6m_V^2 m_T^2 h^2 + 2(m_B^2 - m_T^2 - m_V^2)kb_+ + k^2\right], \\
\mathcal{Z} &= 5m_T^2 m_V^2 k^2. \qquad (21)
\end{aligned}$$

Here we have summed over polarizations of the tensor meson T. The CP asymmetry, $\mathcal{A}_{CP}$, is defined by

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(B \to f) - \mathcal{B}(\bar{B} \to \bar{f})}{\mathcal{B}(B \to f) + \mathcal{B}(\bar{B} \to \bar{f})}, \qquad (22)$$

where B and f denote b quark and a generic final state, respectively.

In passing, we present a set of relations between a flavor SU(3) amplitude involved in $B \to VT$ decays and a corresponding amplitude in the generalized factorization, which bridge both approaches in $B \to VT$ decays as follows [13] (Note that all the SU(3) amplitudes with the subscript P, such as $T_P^{(\prime)}$ etc., vanish because these are proportional to the matrix element $\langle T|j^\mu|0\rangle$.):

$$\begin{aligned}
T_T^{(\prime)} &= \mathrm{i}\frac{G_F}{\sqrt{2}} V_{ub}^* V_{ud(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) a_1, \\
C_T^{(\prime)} &= \mathrm{i}\frac{G_F}{\sqrt{2}} V_{ub}^* V_{ud(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) a_2, \\
S_T^{(\prime)} &= -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{tb}^* V_{td(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) \\
&\quad \times (a_3 + a_5), \\
P_T^{(\prime)} &= -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{tb}^* V_{td(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) a_4, \\
P_{\mathrm{EW},T}^{(\prime)} &= -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{tb}^* V_{td(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) \\
&\quad \times \frac{3}{2}(a_7 + a_9), \\
P_{\mathrm{EW},T}^{C(\prime)} &= -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{tb}^* V_{td(s)} (m_V f_V \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to T}(m_V^2)) \\
&\quad \times \frac{3}{2} a_{10}, \qquad (23)
\end{aligned}$$

where

$$\begin{aligned}
&F_{\alpha\beta}^{B\to T}(m_V^2) \\
&= \epsilon_\mu{}^*(p_B + p_T)_\rho \Big[\mathrm{i}h(m_V^2) \cdot \epsilon^{\mu\nu\rho\sigma} g_{\alpha\nu}(p_V)_\beta (p_V)_\sigma \qquad (24) \\
&\quad + k(m_V^2) \cdot \delta^\mu{}_\alpha \delta^\rho{}_\beta + b_+(m_V^2) \cdot (p_V)_\alpha (p_V)_\beta g^{\mu\rho}\Big].
\end{aligned}$$

Using the above relations (23), one can easily write down in the factorization scheme the amplitude of any $B \to VT$ mode shown in Tables 1 and 2. For example, from Table 1 and the relations (23), the amplitude of the process $B^+ \to \rho^+ a_2^0$ can be written as

$$\begin{aligned}
A(B^+ \to \rho^+ a_2^0) &= -\frac{1}{\sqrt{2}}\Bigg(T_T + C_V + P_T - P_V + P_{\mathrm{EW},V} \\
&\quad + \frac{2}{3}P^C_{\mathrm{EW},T} + \frac{1}{3}P^C_{\mathrm{EW},V}\Bigg) \\
&= \frac{G_F}{\sqrt{2}}\left(m_{\rho^+} f_{\rho^+} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^0}(m_{\rho^+}^2)\right) \\
&\quad \times \left[V_{ub}^* V_{ud} a_1 - V_{tb}^* V_{td}(a_4 + a_{10})\right], \qquad (25)
\end{aligned}$$

where we have used the fact that C_V, P_V, $P_{\mathrm{EW},V}$, and $P^C_{\mathrm{EW},V}$ with the subscript V all vanishing in factorization. Expressions for all the amplitudes of $B \to VT$ decays are given in the appendix as calculated in the factorization scheme.

We calculate the branching ratios and CP asymmetries for $B \to VT$ decay modes for various input parameter values [7,11]. The predictions are sensitive to several input parameters, such as the form factors, the strange quark mass, the parameter $\xi \equiv 1/N_c$, the CKM matrix elements and in particular, the weak phase γ. The following

Table 3. The branching ratios for $B \to VT$ decay modes with $\Delta S = 0$. The second and the third columns correspond to the cases of sets of the parameters: $\{\xi = 0.1, m_s = 85$ MeV, $\gamma = 110°\}$ and $\{\xi = 0.1, m_s = 100$ MeV, $\gamma = 65°\}$, respectively. Similarly, the fourth and the fifth columns corresponds to the cases: $\{\xi = 0.3, m_s = 85$ MeV, $\gamma = 110°\}$ and $\{\xi = 0.3, m_s = 100$ MeV, $\gamma = 65°\}$, respectively. The sixth and the seventh columns correspond to the cases: $\{\xi = 0.5, m_s = 85$ MeV, $\gamma = 110°\}$ and $\{\xi = 0.5, m_s = 100$ MeV, $\gamma = 65°\}$, respectively

Decay mode	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$
$B^+ \to \rho^+ a_2^0$	21.93	22.17	19.46	19.70	17.13	17.37
$B^+ \to \rho^+ f_2$	23.33	23.58	20.70	20.95	18.23	18.48
$B^+ \to \rho^+ f_2'$	0.26	0.26	0.23	0.23	0.20	0.20
$B^+ \to \rho^0 a_2^+$	0.84	0.78	0.046	0.033	1.10	1.16
$B^+ \to \omega a_2^+$	0.77	0.77	0.039	0.034	1.18	1.28
$B^+ \to \phi a_2^+$	0.064	0.053	0.006	0.006	0.022	0.012
$B^+ \to \bar{K}^{*0} K_2^{*+}$	0.062	0.041	0.053	0.033	0.045	0.027
$B^0 \to \rho^+ a_2^-$	40.72	41.16	36.13	36.57	31.81	32.26
$B^0 \to \rho^0 a_2^0$	0.39	0.36	0.022	0.015	0.51	0.54
$B^0 \to \rho^0 f_2$	0.42	0.38	0.023	0.016	0.55	0.57
$B^0 \to \rho^0 f_2'$	0.005	0.004	0.0003	0.0002	0.006	0.006
$B^0 \to \omega a_2^0$	0.36	0.36	0.018	0.016	0.55	0.60
$B^0 \to \omega f_2$	0.38	0.38	0.019	0.017	0.58	0.63
$B^0 \to \omega f_2'$	0.004	0.004	0.0002	0.0002	0.006	0.007
$B^0 \to \phi a_2^0$	0.030	0.025	0.003	0.003	0.010	0.006
$B^0 \to \phi f_2$	0.030	0.025	0.003	0.003	0.010	0.006
$B^0 \to \phi f_2'$	0.0004	0.0003	0	0	0.0001	0
$B^0 \to \bar{K}^{*0} K_2^{*0}$	0.12	0.076	0.098	0.062	0.082	0.050

values of the decay constants (in MeV units) are used for our numerical calculations [12,14,15]:

$$f_\rho = 216, \quad f_\omega = 216, \quad f_\phi = 236, \quad f_{K^*} = 222.$$

The values of the form factors for the $B \to T$ transition are calculated in the ISGW model [6].

The branching ratios for $B \to VT$ decay modes with $\Delta S = 0$ are shown in Table 3. Among the $\Delta S = 0$ modes, the decay modes $B^+ \to \rho^+ a_2^0$, $B^+ \to \rho^+ f_2$, and $B^0 \to \rho^+ a_2^-$ have relatively large branching ratios of a few times 10^{-7}. The branching ratio for $B^+ \to \rho^+ f_2'$ is much smaller than that for $B^+ \to \rho^+ f_2$ by about two orders of magnitude, because the former decay rate is proportional to $\sin\phi_T = 0.13$, instead of $\cos\phi_T = 0.99$, which is a proportionality factor of the latter decay rate. This prediction is consistent with that based on flavor SU(3) symmetry. We see that in the factorization scheme the following equality between the branching ratios holds for any set of the parameters given above: $2\mathcal{B}(B^+ \to \rho^+ a_2^0) \approx \mathcal{B}(B^0 \to \rho^+ a_2^-)$, as discussed in (17). (A little deviation from the exact equality arises from breaking of the isospin symmetry.) We also see from Table 3 that $\mathcal{B}(B^+ \to \rho^0 a_2^+)$ is much smaller than $\mathcal{B}(B^+ \to \rho^+ a_2^0)$ by an order of magnitude or even three orders of magnitude depending on the values of the input parameters. This is because in factorization the dominant contribution to the former mode arises from the color-suppressed tree diagram (C_T) and further the C_T destructively interferes with P_T, while the dominant one to the latter mode arises from the color-favored tree diagram (T_T) and the T_T constructively interferes with P_T. We note that $\mathcal{B}(B^+ \to \rho^0 a_2^{+(0)}) \approx \mathcal{B}(B^+ \to \omega a_2^{+(0)})$ and $\mathcal{B}(B^+ \to \rho^0 f_2^{(\prime)}) \approx \mathcal{B}(B^+ \to \omega f_2^{(\prime)})$, as is expected from the fact that ρ^0 and ω have a similar quark content and the decay amplitudes for the modes having ρ^0 in the final state are similar to those for the modes having ω in the final state (some differences appear only in the penguin diagram contributions which are small in $\Delta S = 0$ decays). The branching ratios of most processes are of order of 10^{-8} or less. The CP asymmetries $\mathcal{A}_{CP}$ in $\Delta S = 0$ decays are shown in Table 4. The CP asymmetries for $B^+ \to \rho^0 a_2^+$ and $B^+ \to \omega a_2^+$ can be as large as 27% and 49%, respectively, with the branching ratio of $O(10^{-8})$ for $\xi = 0.5$.

In Table 7, we show the ratio $\mathcal{B}(B \to VT)/\mathcal{B}(B \to PT)$ for $\Delta S = 0$ decays, where the quark contents of V and P are identical. For comparison, we choose the modes $B^+ \to \rho^+ a_2^0$ ($B^+ \to \pi^+ a_2^0$), $B^+ \to \rho^+ f_2$ ($B^+ \to \pi^+ f_2$), and $B^0 \to \rho^+ a_2^-$ ($B^0 \to \pi^+ a_2^-$) in $B \to VT$ ($B \to PT$) whose decay amplitudes have the dominant tree diagram contribution T_T. For these modes, the ratio $\mathcal{B}(B \to VT)/\mathcal{B}(B \to PT)$ can be written

$$\frac{\mathcal{B}(B \to VT)}{\mathcal{B}(B \to PT)} \approx \frac{m_V f_V^2 [\mathcal{X}|\boldsymbol{p}_V|^7 + \mathcal{Y}|\boldsymbol{p}_V|^5 + \mathcal{Z}|\boldsymbol{p}_V|^3]}{2|\boldsymbol{p}_P|^5 m_B^2 f_P^2 [F^{B\to T}(m_P^2)]^2}. \tag{26}$$

In this ratio, the dependence on G_{F}, the CKM matrix elements, and the effective coefficients a_i do not appear.

Table 4. The CP asymmetries for $B \to VT$ decay modes with $\Delta S = 0$. The definitions for the columns are the same as those in Table 3

Decay mode	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$
$B^+ \to \rho^+ a_2^0$	−0.073	−0.070	−0.072	−0.069	−0.071	−0.068
$B^+ \to \rho^+ f_2$	−0.073	−0.070	−0.072	−0.069	−0.071	−0.068
$B^+ \to \rho^+ f_2'$	−0.073	−0.070	−0.072	−0.069	−0.071	−0.068
$B^+ \to \rho^0 a_2^+$	−0.34	−0.36	0.66	0.91	0.27	0.25
$B^+ \to \omega a_2^+$	0.017	0.016	−0.72	−0.79	−0.49	−0.44
$B^+ \to \phi a_2^+$	0	0	0	0	0	0
$B^+ \to \bar{K}^{*0} K_2^{*+}$	0	0	0	0	0	0
$B^0 \to \rho^+ a_2^-$	−0.073	−0.070	−0.072	−0.069	−0.071	−0.068
$B^0 \to \rho^0 a_2^0$	−0.34	−0.36	0.66	0.91	0.27	0.25
$B^0 \to \rho^0 f_2$	−0.34	−0.36	0.66	0.91	0.27	0.25
$B^0 \to \rho^0 f_2'$	−0.34	−0.36	0.66	0.91	0.27	0.25
$B^0 \to \omega a_2^0$	0.017	0.016	−0.72	−0.79	−0.49	−0.44
$B^0 \to \omega f_2$	0.017	0.016	−0.72	−0.79	−0.49	−0.44
$B^0 \to \omega f_2'$	0.017	0.016	−0.72	−0.79	−0.49	−0.44
$B^0 \to \phi a_2^0$	0	0	0	0	0	0
$B^0 \to \phi f_2$	0	0	0	0	0	0
$B^0 \to \phi f_2'$	0	0	0	0	0	0
$B^0 \to \bar{K}^{*0} K_2^{*0}$	0	0	0	0	0	0

Table 5. The branching ratios for $B \to VT$ decay modes with $|\Delta S| = 1$. The definitions for the columns are the same as those in Table 3

Decay mode	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$	$\mathcal{B}(10^{-8})$
$B^+ \to K^{*+} a_2^0$	10.78	5.97	9.74	5.40	8.75	4.88
$B^+ \to K^{*+} f_2$	11.20	6.19	10.11	5.61	9.09	5.06
$B^+ \to K^{*+} f_2'$	0.14	0.078	0.13	0.070	0.11	0.064
$B^+ \to K^{*0} a_2^+$	16.45	16.45	12.97	12.97	9.91	9.91
$B^+ \to \rho^0 K_2^{*+}$	0.59	0.81	0.57	0.55	0.62	0.39
$B^+ \to \omega K_2^{*+}$	5.30	4.70	0.029	0.035	3.91	3.28
$B^+ \to \phi K_2^{*+}$	2.52	2.52	10.39	10.39	23.66	23.66
$B^0 \to K^{*+} a_2^-$	20.48	11.33	18.50	10.27	16.62	9.26
$B^0 \to K^{*0} a_2^0$	7.65	7.65	6.03	6.03	4.61	4.61
$B^0 \to K^{*0} f_2$	7.94	7.94	6.26	6.26	4.78	4.78
$B^0 \to K^{*0} f_2'$	0.10	0.10	0.079	0.079	0.060	0.060
$B^0 \to \rho^0 K_2^{*0}$	0.54	0.75	0.53	0.50	0.57	0.36
$B^0 \to \omega K_2^{*0}$	4.87	4.32	0.027	0.032	3.60	3.02
$B^0 \to \phi K_2^{*0}$	2.34	2.34	9.64	9.64	21.96	21.96

The ratio depends only on the form factors for $B \to T$ calculated in the ISGW model, in addition to the masses of P, V and T, and the decay constants f_P and f_V. Thus, the ISGW model and the factorization scheme can be tested by measuring the above ratio for different modes, as shown in Table 7, in future experiments. Table 7 shows that the ratio for $\Delta S = 0$ decays are indeed insensitive to different values of the input parameters, such as ξ and the weak phase γ, and are in between 0.473 and 0.495.

The branching ratios and CP asymmetries for $|\Delta S| = 1$ decay processes are shown in Table 5 and 6, respectively. In $|\Delta S| = 1$ decays, the relevant penguin diagrams give a dominant contribution to the decay rates. We see that the branching ratios for $|\Delta S| = 1$ decays are in the range between $O(10^{-7})$ and $O(10^{-10})$, similar to those for $\Delta S = 0$ decays. The processes $B^+ \to K^{*+} a_2^0$, $K^{*+} f_2$, $K^{*0} a_2^+$, and $B^0 \to K^{*+} a_2^-$, $K^{*0} a_2^0$, $K^{*0} f_2$ have relatively large branching ratios of $O(10^{-7})$–$O(10^{-8})$, since the amplitudes for these modes have the dominant penguin contribution P_T'. We note that the branching ratios for $B \to \omega K_2^*$ and $B \to \phi K_2^*$ vary strongly depending on ξ. This is mainly because the amplitudes for these modes have the singlet penguin contribution S_T' and the magnitude of S_T' strongly depends on the value of ξ in the factorization scheme. Un-

Table 6. The CP asymmetries for $B \to VT$ decay modes with $|\Delta S| = 1$. The definitions for the columns are the same as those in Table 3

Decay mode	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$
$B^+ \to K^{*+} a_2^0$	−0.15	−0.26	−0.14	−0.25	−0.14	−0.24
$B^+ \to K^{*+} f_2$	−0.15	−0.26	−0.14	−0.25	−0.14	−0.24
$B^+ \to K^{*+} f_2'$	−0.15	−0.26	−0.14	−0.25	−0.14	−0.24
$B^+ \to K^{*0} a_2^+$	0	0	0	0	0	0
$B^+ \to \rho^0 K_2^{*+}$	−0.006	−0.004	0.001	0.001	0.007	0.010
$B^+ \to \omega K_2^{*+}$	−0.035	−0.038	0.107	0.088	−0.041	−0.047
$B^+ \to \phi K_2^{*+}$	0	0	0	0	0	0
$B^0 \to K^{*+} a_2^-$	−0.15	−0.26	−0.14	−0.25	−0.14	−0.24
$B^0 \to K^{*0} a_2^0$	0	0	0	0	0	0
$B^0 \to K^{*0} f_2$	0	0	0	0	0	0
$B^0 \to K^{*0} f_2'$	0	0	0	0	0	0
$B^0 \to \rho^0 K_2^{*0}$	−0.006	−0.004	0.001	0.001	0.007	0.010
$B^0 \to \omega K_2^{*0}$	−0.035	−0.038	0.107	0.088	−0.041	−0.047
$B^0 \to \phi K_2^{*0}$	0	0	0	0	0	0

Table 7. Ratios of the branching ratios for $B \to VT$ and for $B \to PT$ decay modes, where V and P have identical quark contents. The second and the third columns correspond to the cases of sets of the parameters: $\{m_s = 85\,\text{MeV}, \gamma = 110°\}$ and $\{m_s = 100\,\text{MeV}, \gamma = 65°\}$, respectively. In both cases, the values of ξ vary from 0.1 to 0.5

Ratio	$m_s = 85\,\text{MeV}, \gamma = 110°$	$m_s = 100\,\text{MeV}, \gamma = 65°$
$\mathcal{B}(B^+ \to \rho^+ a_2^0)$ / $\mathcal{B}(B^+ \to \pi^+ a_2^0)$	0.482−0.483	0.495
$\mathcal{B}(B^+ \to \rho^+ f_2)$ / $\mathcal{B}(B^+ \to \pi^+ f_2)$	0.472−0.473	0.484−0.485
$\mathcal{B}(B^0 \to \rho^+ a_2^-)$ / $\mathcal{B}(B^0 \to \pi^+ a_2^-)$	0.473−0.474	0.485−0.486
$\mathcal{B}(B^+ \to K^{*+} a_2^0)$ / $\mathcal{B}(B^+ \to K^+ a_2^0)$	2.50−2.55	1.03−1.10
$\mathcal{B}(B^+ \to K^{*+} f_2)$ / $\mathcal{B}(B^+ \to K^+ f_2)$	2.39−2.50	0.99−1.05
$\mathcal{B}(B^0 \to K^{*+} a_2^-)$ / $\mathcal{B}(B^0 \to K^+ a_2^-)$	2.51−2.63	1.04−1.10

like $\Delta S = 0$ decays such as $B \to \omega a_2$ and $B \to \phi a_2$, in $|\Delta S| = 1$ decays such as $B \to \omega K_2^*$ and $B \to \phi K_2^*$ the tree contribution is suppressed compared to the penguin contribution. Further, in the mode $B \to \omega K_2^*$, the amplitude $2S_T'$ is the only strong penguin contribution so that the branching ratio for this mode varies strongly depending on ξ (even though S_T' is expected to be small due to the OZI suppression). In $B \to \phi K_2^*$, the amplitude $P_T' + S_T'$ is the relevant strong penguin contribution, and in factorization S_T' can become comparable (with the opposite sign) to P_T' for certain values of ξ, say, $\xi = 0$ so that the branching ratio for this mode strongly depends on ξ. Table 6 shows the CP asymmetries $\mathcal{A}_{CP}$ in $|\Delta S| = 1$ decays. $\mathcal{A}_{CP}$'s in most modes are expected to be small. In $B^+ \to K^{*+} a_2^0$, $B^+ \to K^{*+} f_2$, and $B^0 \to K^{*+} a_2^-$, $\mathcal{A}_{CP}$ can be about 15%–25% with the branching ratios of $O(10^{-7})$–$O(10^{-8})$.

In Table 7, we show the ratio $\mathcal{B}(B \to VT)/\mathcal{B}(B \to PT)$ for the modes $B^+ \to K^{*+} a_2^0$ ($B^+ \to K^+ a_2^0$), $B^+ \to K^{*+} f_2$ ($B^+ \to K^+ f_2$), and $B^0 \to K^{*+} a_2^-$ ($B^0 \to K^+ a_2^-$) in $B \to VT$ ($B \to PT$) whose amplitudes have the dominant penguin contribution P_T'. For these modes, the ratio $\mathcal{B}(B \to VT)/\mathcal{B}(B \to PT)$ can be *approximately* expressed as (26), but unlike the $\Delta S = 0$ case, in this case, a dependence of the ratio on the weak phase γ and the strange quark mass m_s remains, due to the effect of the suppressed tree diagram T_T' and the m_s-dependence of $\mathcal{B}(B \to PT)$. In the table, the second and the third columns correspond to the cases of sets of the parameters: $\{m_s = 85\,\text{MeV}, \gamma = 110°\}$ and $\{m_s = 100\,\text{MeV}, \gamma = 65°\}$, respectively. In both cases, the values of ξ vary from 0.1 to 0.5. The result shows two different ranges of values of the ratio: in the former case (the second column), the ratio is about 2.5, while in the latter case (the third column), the ratio is about 1.0. Given values of m_s and γ, the ratio is almost independent of the value of ξ.

5 Conclusion

We have analyzed exclusive charmless decays $B \to VT$ in the frameworks of both flavor SU(3) symmetry and generalized factorization. Using the flavor SU(3) symmetry, we have shown that certain decay modes, such as $B^+ \to \rho^+ a_2^0$, $\rho^+ f_2$ and $B^0 \to \rho^+ a_2^-$ in $\Delta S = 0$ decays, and $B^+ \to K^{*+} f_2$, $K^{*0} a_2^+$ and $B^0 \to K^{*+} a_2^-$ in $|\Delta S| = 1$ decays, are expected to have the largest decay rates, so these modes can be preferable to find in future experiments. Certain ways to test the validity of the factorization scheme have been presented by emphasizing interplay between both approaches and carefully combining the predictions from both approaches. We have also shown that B meson decays to two tensor mesons in the final state do not happen in the factorization scheme, which can be tested in future experiments.

We have calculated the branching ratios and CP asymmetries for $B \to VT$ decays, using the *full* effective Hamiltonian including all the penguin operators which are essential to analyze the $|\Delta S| = 1$ processes and to calculate CP asymmetries. We have also used the non-relativistic quark model proposed by Isgur, Scora, Grinstein, and Wise to obtain the form factors describing $B \to T$ transitions. As shown in Tables 3 and 5, the branching ratios vary from $O(10^{-7})$ to $O(10^{-10})$. Consistent with the prediction from the flavor SU(3) analysis, the decay modes such as $B^+ \to \rho^+ a_2^0$, $\rho^+ f_2$, $B^0 \to \rho^+ a_2^-$ and $B^{+(0)} \to K_2^{*0(+)} a_2^{+(-)}$ have branching ratios of order of 10^{-7}. We have identified the decay modes where the CP asymmetries are expected to be large, such as $B^+ \to \rho^0 a_2^+$ and $B^+ \to \omega a_2^+$ in $\Delta S = 0$ decays, and $B^+ \to K^{*+} a_2^0$, $B^+ \to K^{*+} f_2$, and $B^0 \to K^{*+} a_2^-$ in $|\Delta S| = 1$ decays. Due to possible uncertainties in the hadronic form factors of $B \to VT$ and non-factorization effects, the predicted branching ratios could be increased. We have also presented the ratio $\mathcal{B}(B \to VT)/\mathcal{B}(B \to PT)$ for $\Delta S = 0$ and $|\Delta S| = 1$ decays, which primarily depends on the form factors for $B \to T$, especially in the $\Delta S = 0$ case. Thus, measurement of this ratio for different modes in future experiments can test the ISGW modes and the factorization ansatz. Although experimentally challenging, the exclusive charmless decays, $B \to VT$, can probably be carried out in detail at hadronic B experiments such as BTeV and LHC-B, where more than 10^{12} B mesons will be produced per year, as well as at present asymmetric B factories of Belle and Babar.

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Appendix

In this appendix, we present expressions for all the decay amplitudes of $B \to VT$ modes shown in Tables 1 and 2 as calculated in the factorization scheme. Below we use $F_{\alpha\beta}^{B\to T}$ defined in (24).

(1) $B \to VT$ $(\Delta S = 0)$ decays.

$$A(B^+ \to \rho^+ a_2^0) = \frac{G_F}{2}\left(m_{\rho^+} f_{\rho^+} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^0}(m_{\rho^+}^2)\right) \times \{V_{ub}^* V_{ud} a_1 - V_{tb}^* V_{td}(a_4 + a_{10})\}, \quad (27)$$

$$A(B^+ \to \rho^+ f_2) = \frac{G_F}{2}\left(m_{\rho^+} f_{\rho^+} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to f_2}(m_{\rho^+}^2)\right) \times \{V_{ub}^* V_{ud} c a_1 - V_{tb}^* V_{td} c(a_4 + a_{10})\}, \quad (28)$$

$$A(B^+ \to \rho^+ f_2') = \frac{G_F}{2}\left(m_{\rho^+} f_{\rho^+} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to f_2'}(m_{\rho^+}^2)\right) \times \{V_{ub}^* V_{ud} s a_1 - V_{tb}^* V_{td} s(a_4 + a_{10})\}, \quad (29)$$

$$A(B^+ \to \rho^0 a_2^+) = \frac{G_F}{2}\left(m_{\rho^0} f_{\rho^0} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^+}(m_{\rho^0}^2)\right) \times \left\{ V_{ub}^* V_{ud} a_2 - V_{tb}^* V_{td} \times \left[-a_4 + \frac{3}{2}(a_7 + a_9) + \frac{1}{2}a_{10}\right]\right\}, \quad (30)$$

$$A(B^+ \to \omega a_2^+) = \frac{G_F}{2}\left(m_{\omega} f_{\omega} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^+}(m_{\omega}^2)\right) \times \left\{ V_{ub}^* V_{ud} a_2 - V_{tb}^* V_{td} \times \left[2(a_3 + a_5) + a_4 + \frac{1}{2}(a_7 + a_9) - \frac{1}{2}a_{10}\right]\right\}, \quad (31)$$

$$A(B^+ \to \phi a_2^+) = \frac{G_F}{\sqrt{2}}\left(m_{\phi} f_{\phi} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^+}(m_{\phi}^2)\right) \times \left\{ -V_{tb}^* V_{td}\left[(a_3 + a_5) - \frac{1}{2}(a_7 + a_9)\right]\right\}, \quad (32)$$

$$A(B^+ \to \bar{K}^{*0} K_2^{*+}) = \frac{G_F}{\sqrt{2}}\left(m_{\bar{K}^{*0}} f_{\bar{K}^{*0}} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to K_2^{*+}}(m_{\bar{K}^{*0}}^2)\right) \times \left\{ -V_{tb}^* V_{td}\left[a_4 - \frac{1}{2}a_{10}\right]\right\}, \quad (33)$$

$$A(B^+ \to \bar{K}^{*+} \bar{K}_2^0) = 0, \quad (34)$$

$$A(B^0 \to \rho^+ a_2^-) = \frac{G_F}{\sqrt{2}}\left(m_{\rho^+} f_{\rho^+} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^-}(m_{\rho^+}^2)\right) \times [V_{ub}^* V_{ud} a_1 - V_{tb}^* V_{td}(a_4 + a_{10})], \quad (35)$$

$$A(B^0 \to \rho^- a_2^+) = 0, \quad (36)$$

$$A(B^0 \to \rho^0 a_2^0) = \frac{G_F}{2\sqrt{2}}\left(m_{\rho^0} f_{\rho^0} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to a_2^0}(m_{\rho^0}^2)\right) \times \left\{ V_{ub}^* V_{ud} a_2 - V_{tb}^* V_{td}\left[-a_4 + \frac{3}{2}(a_7 + a_9) + \frac{1}{2}a_{10}\right]\right\}, \quad (37)$$

$$A(B^0 \to \rho^0 f_2) = \frac{G_F}{2\sqrt{2}}\left(m_{\rho^0} f_{\rho^0} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to f_2}(m_{\rho^0}^2)\right) \times \left\{ V_{ub}^* V_{ud} c a_2 - V_{tb}^* V_{td} c\left[-a_4 + \frac{3}{2}(a_7 + a_9) + \frac{1}{2}a_{10}\right]\right\}, \quad (38)$$

$$A(B^0 \to \rho^0 f_2') = \frac{G_F}{2\sqrt{2}}\left(m_{\rho^0} f_{\rho^0} \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to f_2'}(m_{\rho^0}^2)\right)$$

$$\times\Bigg\{V_{ub}^*V_{ud}sa_2 -V_{tb}^*V_{td}s\left[-a_4+\frac{3}{2}(a_7+a_9)+\frac{1}{2}a_{10}\right]\Bigg\}, \quad (39)$$

$$A(B^0\to\omega a_2^0)=\frac{G_F}{2\sqrt{2}}\left(m_\omega f_\omega\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^0}(m_\omega^2)\right) \times\Bigg\{V_{ub}^*V_{ud}a_2-V_{tb}^*V_{td}\Bigg[2(a_3+a_5)+a_4 +\frac{1}{2}(a_7+a_9)-\frac{1}{2}a_{10}\Bigg]\Bigg\}, \quad (40)$$

$$A(B^0\to\omega f_2)=\frac{G_F}{2\sqrt{2}}\left(m_\omega f_\omega\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2}(m_{\omega^0}^2)\right) \times\left\{V_{ub}^*V_{ud}ca_2-V_{tb}^*V_{td}c\left[2(a_3+a_5)+a_4 +\frac{1}{2}(a_7+a_9)-\frac{1}{2}a_{10}\right]\right\}, \quad (41)$$

$$A(B^0\to\omega f_2')=\frac{G_F}{2\sqrt{2}}\left(m_\omega f_\omega\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2'}(m_\omega^2)\right) \times\left\{V_{ub}^*V_{ud}sa_2-V_{tb}^*V_{td}s\left[2(a_3+a_5)+a_4 +\frac{1}{2}(a_7+a_9)-\frac{1}{2}a_{10}\right]\right\}, \quad (42)$$

$$A(B^0\to\phi a_2^0)=\frac{G_F}{2}\left(m_\phi f_\phi\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^0}(m_\phi^2)\right) \times\left\{-V_{tb}^*V_{td}\left[(a_3+a_5)-\frac{1}{2}(a_7+a_9)\right]\right\}, \quad (43)$$

$$A(B^0\to\phi f_2)=\frac{G_F}{2}\left(m_\phi f_\phi\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2}(m_\phi^2)\right) \times\left\{-V_{tb}^*V_{td}c\left[(a_3+a_5)-\frac{1}{2}(a_7+a_9)\right]\right\}, \quad (44)$$

$$A(B^0\to\phi f_2')=\frac{G_F}{2}\left(m_\phi f_\phi\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2'}(m_\phi^2)\right) \times\left\{-V_{tb}^*V_{td}s\left[(a_3+a_5)-\frac{1}{2}(a_7+a_9)\right]\right\}, \quad (45)$$

$$A(B^0\to\bar{K}^{*0}K_2^{*0}) =\frac{G_F}{\sqrt{2}}\left(m_{\bar{K}^{*0}}f_{\bar{K}^{*0}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to K_2^{*0}}(m_{\bar{K}^{*0}}^2)\right) \times\left\{-V_{tb}^*V_{td}\left[a_4-\frac{1}{2}a_{10}\right]\right\}, \quad (46)$$

$$A(B^0\to K^{*0}\bar{K}_2^{*0})=0. \quad (47)$$

(2) $B\to VT$ ($|\Delta S|=1$) decays.

$$A(B^+\to K^{*+}a_2^0) =\frac{G_F}{2}\left(m_{K^{*+}}f_{K^{*+}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^0}(m_{K^{*+}}^2)\right) \times\left\{V_{ub}^*V_{us}a_1-V_{tb}^*V_{ts}(a_4+a_{10})\right\}, \quad (48)$$

$$A(B^+\to K^{*+}f_2) =\frac{G_F}{2}\left(m_{K^{*+}}f_{K^{*+}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2}(m_{K^{*+}}^2)\right) \times\left\{V_{ub}^*V_{us}ca_1-V_{tb}^*V_{ts}c(a_4+a_{10})\right\}, \quad (49)$$

$$A(B^+\to K^{*+}f_2') =\frac{G_F}{2}\left(m_{K^{*+}}f_{K^{*+}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to T}(m_V^2)\right) \times\left\{V_{ub}^*V_{us}sa_1-V_{tb}^*V_{ts}s(a_4+a_{10})\right\}, \quad (50)$$

$$A(B^+\to K^{*0}a_2^+) =\frac{G_F}{\sqrt{2}}\left(m_{K^{*0}}f_{K^{*0}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^+}(m_{K^{*0}}^2)\right) \times\left\{-V_{tb}^*V_{ts}\left(a_4-\frac{1}{2}a_{10}\right)\right\}, \quad (51)$$

$$A(B^+\to\rho^+K_2^{*0})=0, \quad (52)$$

$$A(B^+\to\rho^0K_2^{*+}) =\frac{G_F}{2}\left(m_{\rho^0}f_{\rho^0}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to K_2^{*+}}(m_{\rho^0}^2)\right) \times\left\{V_{ub}^*V_{us}a_2-V_{tb}^*V_{ts}\frac{3}{2}(a_7+a_9)\right\}, \quad (53)$$

$$A(B^+\to\omega K_2^{*+})=\frac{G_F}{2}\left(m_\omega f_\omega\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to K_2^{*+}}(m_\omega^2)\right) \times\Bigg\{V_{ub}^*V_{us}a_2 -V_{tb}^*V_{ts}\left[2(a_3+a_5)+\frac{1}{2}(a_7+a_9)\right]\Bigg\}, \quad (54)$$

$$A(B^+\to\phi K_2^{*+})=\frac{G_F}{\sqrt{2}}\left(m_\phi f_\phi\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to K_2^{*+}}(m_\phi^2)\right) \times\Bigg\{-V_{tb}^*V_{ts}\Bigg[a_3+a_4+a_5 -\frac{1}{2}(a_7+a_9+a_{10})\Bigg]\Bigg\}, \quad (55)$$

$$A(B^0\to K^{*+}a_2^-) =\frac{G_F}{\sqrt{2}}\left(m_{K^{*+}}f_{K^{*+}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^-}(m_{K^{*+}}^2)\right) \times\left\{V_{ub}^*V_{us}a_1-V_{tb}{}^*V_{ts}(a_4+a_{10})\right\}, \quad (56)$$

$$A(B^0\to K^{*0}a_2^0)=\frac{G_F}{2}\left(m_{K^{*0}}f_{K^{*0}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to a_2^0}(m_{K^{*0}}^2)\right) \times\left\{-V_{tb}^*V_{ts}\left(a_4-\frac{1}{2}a_{10}\right)\right\}, \quad (57)$$

$$A(B^0\to K^{*0}f_2)=\frac{G_F}{2}\left(m_{K^{*0}}f_{K^{*0}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2}(m_{K^{*0}}^2)\right) \times\left\{-V_{tb}^*V_{ts}c\left(a_4-\frac{1}{2}a_{10}\right)\right\}, \quad (58)$$

$$A(B^0\to K^{*0}f_2')=\frac{G_F}{2}\left(m_{K^{*0}}f_{K^{*0}}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to f_2'}(m_{K^{*0}}^2)\right) \times\left\{-V_{tb}^*V_{ts}s\left(a_4-\frac{1}{2}a_{10}\right)\right\}, \quad (59)$$

$$A(B^0\to\rho^-K_2^{*+})=0, \quad (60)$$

$$A(B^0\to\rho^0K_2^{*0})=\frac{G_F}{2}\left(m_{\rho^0}f_{\rho^0}\epsilon^{*\alpha\beta}F_{\alpha\beta}^{B\to K_2^{*0}}(m_{\rho^0}^2)\right)$$

$$\times \left\{ V_{ub}^* V_{us} a_2 - V_{tb}^* V_{ts} \frac{3}{2}(a_9 + a_7) \right\}, \quad (61)$$

$$A(B^0 \to \omega K_2^{*0}) = \frac{G_F}{2} \left(m_\omega f_\omega \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to K_2^{*0}}(m_\omega^2) \right)$$
$$\times \left\{ V_{ub}^* V_{us} a_2 \right.$$
$$\left. - V_{tb}^* V_{ts} \left[2(a_3 + a_5) + \frac{1}{2}(a_7 + a_9) \right] \right\}, \quad (62)$$

$$A(B^0 \to \phi K_2^{*0}) = \frac{G_F}{\sqrt{2}} \left(m_\phi f_\phi \epsilon^{*\alpha\beta} F_{\alpha\beta}^{B\to K_2^{*0}}(m_\phi^2) \right)$$
$$\times \left\{ -V_{tb}^* V_{ts} \left[a_3 + a_4 + a_5 \right.\right.$$
$$\left.\left. -\frac{1}{2}(a_7 + a_9 + a_{10}) \right] \right\}. \quad (63)$$

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