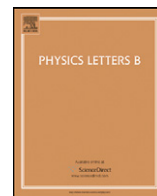


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B decays dominated by ω - ϕ mixing

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ABSTRACT

Recently Belle has established the 90% confidence level (CL) upper limit $\mathcal{B} < 9.4 \times 10^{-7}$ for the branching ratio for $B^0 \rightarrow J/\psi\phi$, a process expected to be suppressed by the Okubo-Zweig-Iizuka (OZI) rule disfavoring disconnected quark diagrams. We use information on ω - ϕ mixing to establish likely lower bounds on this and related processes. We find that the Belle result is about a factor of five above our limit, while other decays such as $B^0 \rightarrow \bar{D}^0\phi$ and $B^+ \rightarrow \pi^+\phi$, for which upper limits have been obtained by BaBar, could be observable with similar improvements in data. We argue that a significant enhancement of our predicted decay rates by rescattering is unlikely.

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Certain B meson decay processes are expected to be suppressed, as they involve either the participation of a spectator quark or, equivalently in terms of flavor topology, the rescattering of final states into one another. A number of such processes were suggested in Ref. [1]. Recently the Belle Collaboration has greatly improved upper limits on one such process, the decay $B^0 \rightarrow J/\psi\phi$, finding a 90% CL upper limit for the branching ratio of $\mathcal{B} < 9.4 \times 10^{-7}$ [2]. This process is expected to be suppressed by the Okubo-Zweig-Iizuka (OZI) rule disfavoring disconnected quark diagrams [3]. In the present Letter we evaluate one potential mechanism for production of such a final state, the existence of ω - ϕ mixing, and find that it leads to a predicted branching ratio about a factor of five below the present upper limit. We also evaluate the effect of this mixing upon several other processes and find that for $B^0 \rightarrow \bar{D}^0\phi$ and $B^+ \rightarrow \pi^+\phi$ a similar improvement in data should lead to observable signals.

Extensive discussions of ω - ϕ mixing have been given in Refs. [4–8]. We shall neglect isospin-violation and admixtures with the ρ . Then one can parametrize ω - ϕ mixing in terms of an angle δ such that the physical ω and ϕ are related to the ideally mixed states $\omega^I \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\phi^I \equiv s\bar{s}$ by

$$\begin{pmatrix} \omega \\ \phi \end{pmatrix} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} \omega^I \\ \phi^I \end{pmatrix}. \quad (1)$$

A simplified analysis [4] implies a mixing angle of $\delta = -(3.34 \pm 0.17)^\circ$, while the most recent treatment [8] implies an energy-

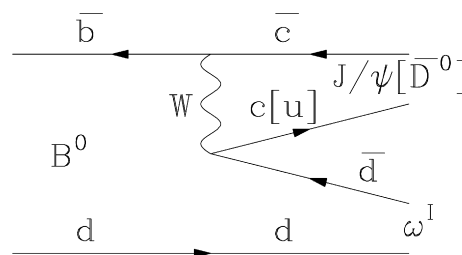


Fig. 1. Quark diagrams for OZI-allowed $B^0 \rightarrow J/\psi\omega^I$ and $B^0 \rightarrow \bar{D}^0\phi^I$.

dependent mixing which varies from -0.45° at the ω mass to -4.64° at the ϕ mass.

A systematic study of the effects of ω - ϕ mixing on hadronic decays of non-strange B mesons, $B^0 \equiv \bar{b}d$, $B^+ \equiv \bar{b}u$, requires considering the three $\Delta S = 0$ quark subprocesses, $\bar{b} \rightarrow \bar{c}u\bar{d}$, $\bar{b} \rightarrow \bar{c}c\bar{d}$ and $\bar{b} \rightarrow \bar{u}u\bar{d}$. Each one of these subprocesses leads to OZI-allowed decays involving ω^I , while decays into final states with ϕ^I are OZI-suppressed. Quark diagrams describing two examples of OZI-allowed decays, $B^0 \rightarrow J/\psi\omega^I$ and $B^0 \rightarrow \bar{D}^0\omega^I$, and corresponding OZI-suppressed decays, $B^0 \rightarrow J/\psi\phi^I$ and $B^0 \rightarrow \bar{D}^0\phi^I$, are shown in Figs. 1 and 2. The first two processes are described by color-suppressed tree diagrams, while the other two processes involve W -exchange diagrams, to which an $s\bar{s}$ pair is attached through three gluons.

The situation in decays of $B_s \equiv \bar{b}s$ is the opposite relative to that in non-strange B decays. That is, the ω and ϕ exchange roles. Here one considers the $\Delta S = 1$ quark subprocess $\bar{b} \rightarrow \bar{c}c\bar{s}$ which leads to OZI-allowed decays involving ϕ^I and OZI-suppressed decays with ω^I . (The quark subprocess $\bar{b} \rightarrow \bar{c}u\bar{s}$ leads through W -exchange diagrams to OZI-allowed B_s decays involving ω^I includ-

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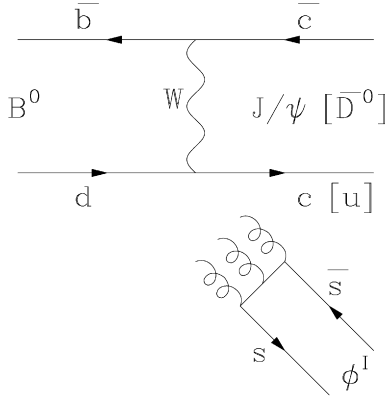


Fig. 2. Quark diagrams for OZI-suppressed $B^0 \rightarrow J/\psi\phi^I$ and $B^0 \rightarrow \bar{D}^0\phi^I$.

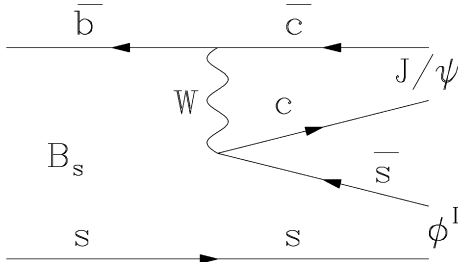


Fig. 3. Quark diagrams for OZI-allowed $B_s \rightarrow J/\psi\phi^I$.

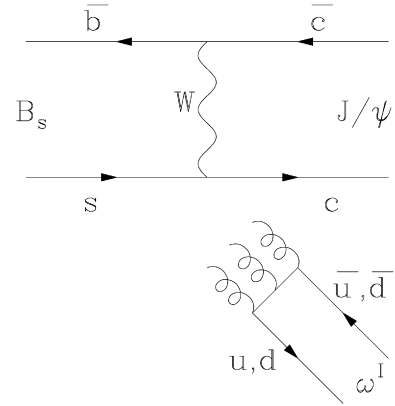


Fig. 4. Quark diagrams for OZI-suppressed $B_s \rightarrow J/\psi\omega^I$.

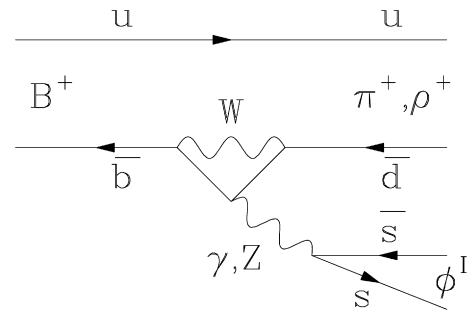


Fig. 5. Electroweak penguin diagram for OZI-suppressed $B^+ \rightarrow \pi^+\phi^I$ and $B^+ \rightarrow \rho^+\phi^I$.

ing $\bar{D}^0\omega^I$.) Examples of quark diagrams describing the OZI-allowed decay $B_s \rightarrow J/\psi\phi^I$ and the corresponding OZI-suppressed decay $B_s \rightarrow J/\psi\omega^I$ are shown in Figs. 3 and 4. As in the above examples of B^0 decays, the first process is governed by a color-suppressed tree amplitude, while the second decay is described by a W-exchange diagram, to which a $u\bar{u}$ or $d\bar{d}$ pair is attached by three gluons.

Neglecting contributions of OZI-suppressed amplitudes and small phase space differences between processes with ω or ϕ in the final state, Eq. (1) implies

$$\mathcal{B}(B^{0,+} \rightarrow X^{0,+}\phi) = \tan^2 \delta \mathcal{B}(B^{+0} \rightarrow X^{+0}\omega), \quad (2)$$

$$\mathcal{B}(B_s \rightarrow X^0\omega) = \tan^2 \delta \mathcal{B}(B_s \rightarrow X^0\phi). \quad (3)$$

The examples shown in Figs. 1 and 3 correspond to $X^0 = J/\psi$, \bar{D}^0 in B^0 decays and $X^0 = J/\psi$ in B_s decays.

In Table 1 we list OZI-allowed branching ratios of B^0 , B^+ and B_s decays, for which nonzero values have been measured, and upper limits on corresponding OZI-suppressed decays. The upper left part of the table, addressing non-strange B mesons, includes also processes involving ρ^0 , for which branching ratios are expected to be approximately equal to corresponding processes with ω . (See Fig. 1.) The approximately equal decay rates measured for $B^0 \rightarrow \bar{D}^0\rho^0$ and $B^0 \rightarrow \bar{D}^0\omega$ confirm this assumption. OZI-allowed branching ratios for B_s decays involving ϕ are listed in the lower left part of the Table 1.

Using Eqs. (2) and (3) with a universal value of $\delta = -4.64^\circ$ and the measured OZI-allowed branching ratios, we obtain predictions for the OZI-suppressed rates shown in the right-hand column of Table 1. Values in parentheses, quoting predictions for OZI-suppressed B_s decays involving ω , are obtained for the small mixing angle $\delta = -0.45^\circ$ [8]. Predictions for B^0 and B^+ decays are compared with current upper bounds measured for these branching ratios. We note that the predictions for $\mathcal{B}(B^0 \rightarrow \bar{D}^0\phi)$, $\mathcal{B}(B^0 \rightarrow J/\psi\phi)$ and $\mathcal{B}(B^+ \rightarrow \pi^+\phi)$ are about a factor five smaller than the current upper limits on these branching ratios.

While most OZI-allowed processes in Table 1 are described by color-suppressed tree diagrams as shown in Figs. 1 and 3, the CKM-suppressed charmless decays $B^+ \rightarrow \pi^+\omega$ and $B^+ \rightarrow \rho^+\omega$ are dominated by color-allowed tree diagrams [20,21]. Contributions to these processes from color-suppressed tree diagrams are considerably smaller. This is demonstrated by 90% CL upper limits measured for corresponding color-suppressed branching ratios, $\mathcal{B}(B^0 \rightarrow \pi^0\omega) < 0.12 \times 10^{-5}$ [22] and $\mathcal{B}(B^0 \rightarrow \rho^0\omega) < 0.15 \times 10^{-5}$ [16], which are a factor six or seven below $\mathcal{B}(B^+ \rightarrow \pi^+\omega)$ and $\mathcal{B}(B^+ \rightarrow \rho^+\omega)$ given in Table 1. The corresponding OZI-suppressed amplitudes for $B^+ \rightarrow \pi^+\phi$ and $B^+ \rightarrow \rho^+\phi$ each obtain an electroweak penguin contribution [23] and a contribution from a singlet penguin diagram [24], shown in Figs. 5 and 6, respectively. These amplitudes have been calculated in Refs. [25] and [26] within the framework of QCD factorization neglecting ω - ϕ mixing. Branching ratios $\mathcal{B}(B^+ \rightarrow \pi^+\phi) = (2 - 10) \times 10^{-9}$ and $\mathcal{B}(B^+ \rightarrow \rho^+\phi) = (1 - 3) \times 10^{-8}$ were obtained, considerably smaller than the two corresponding predictions in Table 1 originating in ω - ϕ mixing.

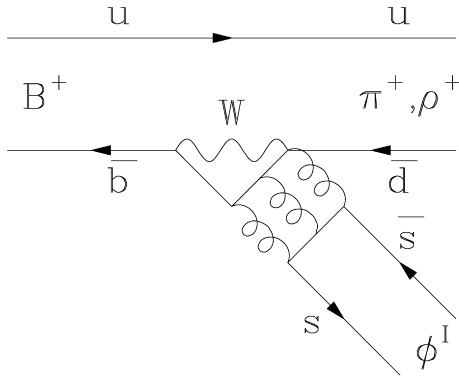
Assuming that small OZI-suppressed amplitudes do not interfere destructively with amplitudes due to ω - ϕ mixing, the predictions presented in Table 1 for branching ratios of OZI-suppressed decays should be considered as likely lower bounds. In principle, these branching ratios may be enhanced by rescattering through intermediate states with larger decay rates. This possibility had been envisaged a few years before starting the operation of e^+e^- B factories [1]. We will now argue that experimental evidence obtained in certain experiments indicates that a significant enhancement by rescattering is unlikely in OZI-suppressed and other suppressed decays.

Consider the decay $B^0 \rightarrow D_s^- K^+$, which is governed by a W-exchange amplitude represented by a quark subprocess $(\bar{b}d) \rightarrow (\bar{c}u)$, associated with a popping of an $s\bar{s}$ pair out of the vacuum. This exchange amplitude is expected to be suppressed by

Table 1

Comparison of some OZI-allowed and OZI-suppressed branching ratios, in units of 10^{-5} and 10^{-7} , respectively. Averages are taken from Ref. [9]. Upper limits are 90% CL. Predictions are based on an ω - ϕ mixing angle $\delta = -4.64^\circ$. Parentheses denote predictions based on the very small admixture of $s\bar{s}$ expected in the ω in Ref. [8]

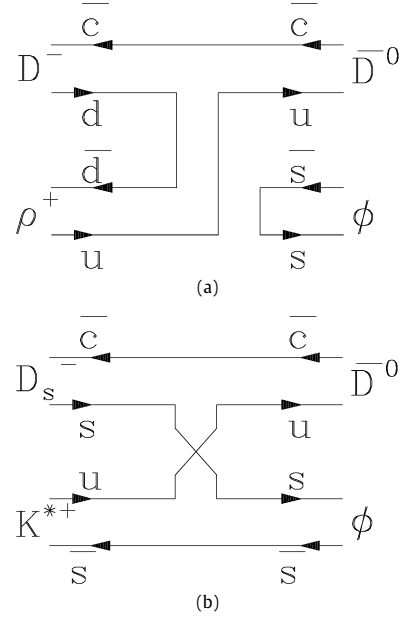
Quark subprocess	OZI-allowed		OZI-suppressed		
	Decay mode	\mathcal{B} (10^{-5})	Decay mode	\mathcal{B} (10^{-7})	
				Upper limit	Predicted
$\bar{b} \rightarrow \bar{c}u\bar{d}$	$B^0 \rightarrow \bar{D}^0 \rho^0$	32 ± 5 [10]	$B^0 \rightarrow \bar{D}^0 \phi$	< 116 [11]	21 ± 3
	$\bar{D}^0 \omega$	25.9 ± 3.0 [12]	$\bar{D}^0 \phi$	< 116 [11]	17 ± 2
	$\bar{D}^{*0} \omega$	27 ± 8 [12]	$\bar{D}^{*0} \phi$	-	18 ± 5
$\bar{b} \rightarrow \bar{c}c\bar{d}$	$J/\psi \rho^0$	2.7 ± 0.4 [13]	$J/\psi \phi$	< 9.4 [2]	1.8 ± 0.3
	$\bar{b} \rightarrow \bar{u}u\bar{d}$	$B^+ \rightarrow \pi^+ \omega$	0.69 ± 0.05 [14]	$B^+ \rightarrow \pi^+ \phi$	< 2.4 [15]
$\rho^+ \omega$		$1.06^{+0.26}_{-0.23}$ [16]	$\rho^+ \phi$	< 160 [17]	0.7 ± 0.2
$\bar{b} \rightarrow \bar{c}c\bar{s}$	$B_s \rightarrow J/\psi \phi$	93 ± 33 [18]	$B_s \rightarrow J/\psi \omega$	-	61 ± 22 (0.6)
	$\psi(2S) \phi$	48 ± 22 [19]	$\psi(2S) \omega$	-	32 ± 15 (0.3)

**Fig. 6.** Singlet penguin diagram for OZI-suppressed $B^+ \rightarrow \pi^+ \phi'$ and $B^+ \rightarrow \rho^+ \phi'$.

an order of magnitude ($\sim \Lambda_{\text{QCD}}/m_b$) relative to the corresponding color-favored tree amplitude for $B^0 \rightarrow D^- \pi^+$ induced by the same quark subprocess, $\bar{b} \rightarrow \bar{c}u\bar{d}$ [20,27,28]. This would imply $\mathcal{B}(B^0 \rightarrow D_s^- K^+)/\mathcal{B}(B^0 \rightarrow D^- \pi^+) \sim 10^{-2}$. Rescattering through dynamically favored intermediate states including $B^0 \rightarrow D^- \pi^+ \rightarrow D_s^- K^+$ and rescattering through other intermediate $C = -1$, $S = 0$ states, with decay branching ratios at a level of a fraction of a percent, could enhance the branching ratio for $B^0 \rightarrow D_s^- K^+$ relative to the above expectation. Experimentally, one finds [29] $\mathcal{B}(B^0 \rightarrow D_s^- K^+) = (2.9 \pm 0.5) \times 10^{-5}$, in comparison with [9] $\mathcal{B}(B^0 \rightarrow D^- \pi^+) = (2.68 \pm 0.13) \times 10^{-3}$ which is two orders of magnitude larger. That is, rescattering effects do not enhance the rate for $B^0 \rightarrow D_s^- K^+$ beyond the estimate based on an exchange amplitude.

One possible conclusion is that a significant enhancement of diagrammatically suppressed decay rates by rescattering requires intermediate states with rates which are larger than the suppressed rates by *more than two orders of magnitude*. This requirement seems to follow from the multi-channel nature of the rescattering process occurring between the initial B meson and the final state to which it decays. Examples for processes which have been shown to need an enhancement by rescattering are the decays $B \rightarrow K\pi$ [30]. The short-distance loop-suppressed penguin amplitude dominating these processes is too small to account for the measured decay rates and requires an enhancement by long-distance rescattering [31]. The branching ratios of intermediate states including $B \rightarrow D_s^{(*)-} D^{(*)+}$ are at a percent level, *three orders of magnitude* larger than the branching ratios calculated for $B \rightarrow K\pi$ using short-distance physics. This is sufficient for a significant enhancement of the $B \rightarrow K\pi$ decay rates relative to this calculation.

A well-known charmless B decay process dominated by a W -exchange amplitude is $B^0 \rightarrow K^+ K^-$ [1,20]. This process receives rescattering contributions from tree-dominated intermediate states including $\pi^+ \pi^-$ with a branching ratio [9] $\mathcal{B}(B^0 \rightarrow \pi^+ \pi^-) =$

**Fig. 7.** Quark diagrams for (a) OZI-suppressed rescattering $D^- \rho^+ \rightarrow \bar{D}^0 \phi$, (b) OZI-allowed rescattering $D_s^- K^{*+} \rightarrow \bar{D}^0 \phi$.

$(5.13 \pm 0.24) \times 10^{-6}$. Assuming an order of magnitude suppression of the exchange amplitude relative to a tree amplitude as in $B^0 \rightarrow D_s^- K^+$, and using the above criterion for no significant enhancement by rescattering, one expects $\mathcal{B}(B^0 \rightarrow K^+ K^-) \sim 5 \times 10^{-8}$, almost an order of magnitude below the current 90% CL upper limit of [32] 4.1×10^{-7} . Similarly, using [9] $\mathcal{B}(B^0 \rightarrow \rho^+ \rho^-) = (2.42 \pm 0.31) \times 10^{-5}$, we predict $\mathcal{B}(B^0 \rightarrow K^{*+} K^{*-}) \sim 2 \times 10^{-7}$. Very recently an upper limit at 90% CL has been measured [33], $\mathcal{B}(B^0 \rightarrow K^{*+} K^{*-}) < 2.0 \times 10^{-6}$, an order of magnitude above our prediction.

Consider now the OZI-suppressed decay $B^0 \rightarrow \bar{D}^0 \phi$. The quark diagram for this process shown in Fig. 2 describes an exchange amplitude $(\bar{b}d) \rightarrow (\bar{c}u)$ as in $B^0 \rightarrow D_s^- K^+$, to which a pair of $s\bar{s}$ is attached by three gluons. The above argument for no significant rescattering effects in $B^0 \rightarrow D_s^- K^+$ implies the absence of such effects also in $B^0 \rightarrow \bar{D}^0 \phi$. To demonstrate this explicitly, let us consider the two kinds of intermediate states through which rescattering into $\bar{D}^0 \phi$ can occur:

1. States dominated by tree amplitudes such as $D^- \rho^+$ [$(\bar{c}d)(\bar{d}u)$]. Rescattering through these intermediate states into $\bar{D}^0 \phi$ [$(\bar{c}u)(\bar{s}s)$] is OZI-suppressed [see Fig. 7(a)] and is not expected to enhance the rate for $B^0 \rightarrow \bar{D}^0 \phi$.

2. States governed by exchange amplitudes including $D_s^- K^{*+}$ [$(\bar{c}s)(\bar{s}u)$]. Rescattering through these states into $\bar{D}^0 \phi$ [$(\bar{c}u)(\bar{s}s)$] is

OZI-allowed [see Fig. 7(b)]. This rescattering is not expected to enhance the predicted branching ratio, $\mathcal{B}(B^0 \rightarrow \bar{D}^0\phi) \simeq 2 \times 10^{-6}$, because $\mathcal{B}(B^0 \rightarrow D_s^- K^{*+})$ is expected to be only one order of magnitude larger, assuming that it does not differ much from $\mathcal{B}(B^0 \rightarrow D_s^- K^+) = (2.9 \pm 0.5) \times 10^{-5}$.

A similar situation exists in $B^0 \rightarrow J/\psi\phi$. Here OZI-suppressed rescattering occurs through intermediate tree-dominated states including $D^{(*)+}D^{(*)-}$, while OZI-allowed rescattering involves intermediate states such as $D_s^{(*)+}D_s^{(*)-}$. B^0 decays into the latter states are dominated by exchange amplitudes, which are expected to be suppressed by about an order of magnitude relative to the tree amplitudes in $B^0 \rightarrow D^{(*)+}D^{(*)-}$. Using the suppression measured for the exchange amplitude in $B^0 \rightarrow D_s^- K^+$, this implies, for instance [34], $\mathcal{B}(B^0 \rightarrow D_s^+ D_s^-) = (4.0_{-1.4}^{+1.8}) \times 10^{-6}$, an order of magnitude below the current upper limit on this branching ratio [35]. This branching ratio is only twenty times larger than the value predicted for $\mathcal{B}(B^0 \rightarrow J/\psi\phi)$, which is expected to be insufficient for an enhancement of the latter branching ratio by rescattering through this class of intermediate states.

In the case of $B \rightarrow \pi^+\phi$ (or $B^+ \rightarrow \rho^+\phi$) the situation is slightly different, but the condition for a significant enhancement by rescattering is also not met. The final state $\pi^+\phi$ may be reached by OZI-suppressed rescattering through intermediate states such as $\pi^+\rho^0$, or by OZI-allowed rescattering through states including $K^+\bar{K}^{*0}$. B^+ decay into the latter mode is dominated by a suppressed $\Delta S = 0$ penguin amplitude [21] implying a small branching ratio. The current 90% CL upper limit [36], $\mathcal{B}(B^+ \rightarrow K^+\bar{K}^{*0}) < 1.1 \times 10^{-6}$, shows that this branching ratio is at most twenty-five times larger than the predicted $\mathcal{B}(B^+ \rightarrow \pi^+\phi)$. As discussed above, this is insufficient for enhancing the latter branching ratio by rescattering.

In conclusion, we have studied the consequences of ω - ϕ mixing in OZI-suppressed hadronic decays of B and B_s mesons. We calculated branching ratios for B decays involving ϕ , which in the cases of $B^0 \rightarrow \bar{D}^0\phi$, $B^0 \rightarrow J/\psi\phi$ and $B^+ \rightarrow \pi^+\phi$ are each about a factor of five below the corresponding current upper limits. We used the observed suppression of branching ratios for decays dominated by W -exchange including $B^0 \rightarrow D_s^- K^+$ to argue that a significant enhancement of these rates by rescattering is unlikely. Thus, the above three processes are predicted to be detectable with a factor of five increase in data. Effects of ω - ϕ mixing in OZI-suppressed B_s decays involving ω are much smaller than in non-strange B decays if one assumes a very small admixture of $s\bar{s}$ in the ω as suggested in Ref. [8]. The predicted branching ratios become a factor two smaller than in Table 1 for an energy-independent ω - ϕ mixing angle of $\delta = -3.34^\circ$ [4].

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