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Estimating the Branching Fraction for $B^0 \to \psi(2S)\pi^0$ Decay

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Abstract. I present estimates of the branching fractions in the non-leptonic charmonium two-body decay rates for $B^0 \to \psi(2S)\pi^0$ decay and the same decays of $B^+ \to \psi(2S)\pi^+$, $B^0 \to \psi(2S)K^0$ and $B^+ \to \psi(2S)K^+$. These estimates are based on a generalized factorization approach making use of leading order (LO) and next-to-leading order (NLO) contributions. I find that when the large enhancements from the known NLO contributions by using the QCD factorization approach are taken into account, the branching ratios are the following: $\text{BR}(B^0 \to \psi(2S)\pi^0) = (1.067 \pm 0.059) \times 10^{-5}$, $\text{BR}(B^+ \to \psi(2S)\pi^+) = (2.134 \pm 0.0.118) \times 10^{-5}$, $\text{BR}(B^0 \to \psi(2S)K^0) = (6.344 \pm 0.376) \times 10^{-4}$ and $\text{BR}(B^+ \to \psi(2S)K^+) = (6.344 \pm 0.376) \times 10^{-4}$, while the experimental results are $(1.17 \pm 0.17) \times 10^{-5}$, $(2.44 \pm 0.30) \times 10^{-5}$, $(6.20 \pm 0.50) \times 10^{-4}$ and $(6.39 \pm 0.33) \times 10^{-4}$ respectively. All estimates are in good agreement with the experimental results.

INTRODUCTION

B-meson decays to two-body final states containing a charmonium resonance such as a $\psi(2S)$ offer a powerful way of studying electroweak transitions. Such decays probe charmonium properties and play a role in the study of CP violation and mixing in the neutral B system. Recently the Belle collaboration have reported a measurement of the $B^0 \to \psi(2S)\pi^0$ branching fraction based on the full $\gamma(4S)$ data set of $772 \times 10^6 B\bar{B}$ pairs collected by the Belle detector at the KEKB asymmetric-energy e^+e^- collider [1]. From the fit to the data containing 1090 $B^0 \to \psi(2S)\pi^0$ candidates, they have obtained the bias-corrected branching fraction

$$\text{BR}\big(B^0 \to \psi(2S)\pi^0\big) = \big(1.17 \pm 0.17(\text{stat}) \pm 0.08(\text{syst})\big) \times 10^{-5}. \tag{1}$$

The branching fraction corresponds to 85 signal events, of which 38 are leptonic and 47 are hadronic, 628 events originate from other $b \to (c\bar{c})q$ decays and 377 events belong to the combinatorial background. All uncertainties here are statistical. Fit projections to the data are shown in Figure 1. Within the factorization approach, I calculate the amplitudes for the $B^0 \to \psi(2S)\pi^0$ decay and the same decays of $B^+ \to \psi(2S)\pi^+$, $B^0 \to \psi(2S)K^0$ and $B^+ \to \psi(2S)K^+$ by using a color-suppressed internal W-emission and a penguin diagrams. Since the CP-violating asymmetry for $B^0 \to \psi(2S)\pi^0$ decay is not available, the values of the $B^+ \to \psi(2S)\pi^+$, $B^0 \to \psi(2S)K^0$ and $B^+ \to \psi(2S)K^+$ are considered for comparison with the main decay in the future. Under the naive and QCD factorization at LO and NLO schemes, the branching ratios are calculated, by using NLO scheme at $\mu = 2m_b$ scale they become

$$\begin{aligned} \text{BR}(B^0 \to \psi(2S)\pi^0) &= (1.067 \pm 0.059) \times 10^{-5}, \\ \text{BR}(B^+ \to \psi(2S)\pi^+) &= (2.134 \pm 0.118) \times 10^{-5}, \\ \text{BR}(B^{0(+)} \to \psi(2S)K^{0(+)}) &= (6.344 \pm 0.376) \times 10^{-4}. \end{aligned} \tag{2}$$

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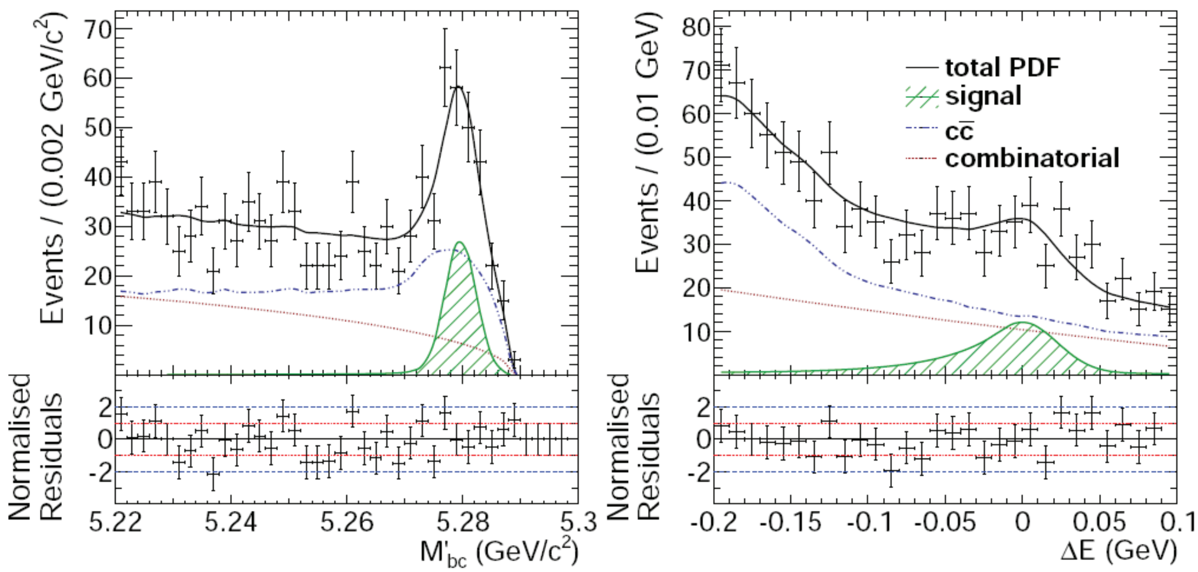

FIGURE 1. Projections of the fit to the $B^0 \to \psi(2S)\pi^0$ data in the entire fit region onto M'_{bc} (left) and ΔE (right). Points with error bars represent the data and the solid black curves represent the fit results. Green hatched curves show the $B^0 \to \psi(2S)\pi^0$ signal component, blue dash-dotted curves show the $c\bar{c}$ background component, and red dotted curves indicate the combinatorial background.

AMPLITUDE OF THE $B^0 \to \psi(2S)\pi^0$ AND $B^0 \to \psi(2S)K^0$ DECAYS

In the factorization approach, Feynman diagrams for $B^0 \to \psi(2S)\pi^0$ and $B^0 \to \psi(2S)K^0$ decays are shown in Figure 2, there are a current-current and a QCD penguin amplitudes for these decay modes, it has

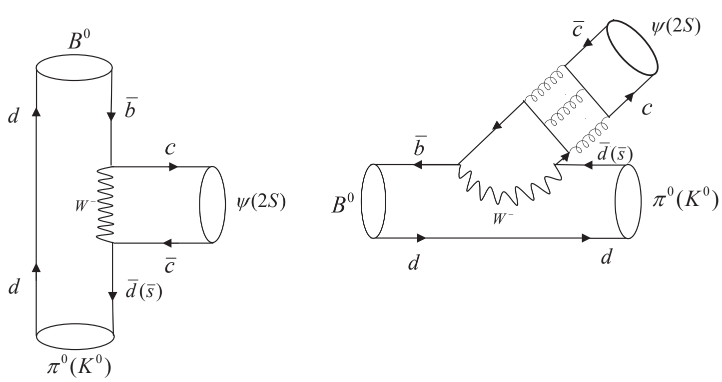

FIGURE 2. Quark diagram illustration the process $B^0 \to \psi(2S)\pi^0$ and $B^0 \to \psi(2S)K^0$ decays. If the spectator quarks of d to be changed with u, the decays of $B^+ \to \psi(2S)\pi^+$ and $B^+ \to \psi(2S)K^+$ can be obtained.

been advocated that the new internal W-emission contribution coming from the Cabibbo-allowed process $B \to c\bar{c}d(s)$ followed by a conversion of the $c\bar{c}$ pair into the $\psi(2S)$ via two gluon exchanges is potentially important since its mixing angle $V_{cb}V^*_{cd(s)}$ is as large as that of the penguin amplitude and yet its Wilson coefficient a_2 is larger than that of penguin operators. In the color-suppressed internal W-emission tree (a_2), penguin (a_3) and electro-weak penguin (a_5, a_7 and a_9) diagrams both π^0 and K^0 mesons are placed in the form factor, the meson of $\psi(2S)$ is produced from the vacuum state, therefore the amplitudes of these decays consist of $\langle B^0 \to \pi^0\rangle$ and $\langle B^0 \to K^0\rangle$ multiplied by $\langle 0 \to \psi(2S)\rangle$ which are factorizable terms. The form factor $\langle P(p')|V_\mu|B(p)\rangle$ is parametrized as [2]

$$\langle M(p_M)|V_\mu|B(p_B)\rangle = \big[(p_B + p_M)_\mu - \frac{m_B^2 - m_M^2}{q^2} q_\mu\big] F_1(q^2) + \frac{m_B^2 - m_M^2}{q^2} q_\mu F_0(q^2), \tag{3}$$

where $M = \pi, K$ and $q = p_B - p_M$. The decay constant is defined as [3]

$$\langle 0|V_\mu|\psi(2S)(\epsilon_{\psi(2S)}, p_{\psi(2S)})\rangle = f_{\psi(2S)} m_{\psi(2S)} \epsilon_{\psi(2S)\mu}. \tag{4}$$

Because of $q_\mu = p_{\psi(2S)\mu}$ and $\epsilon_{\psi(2S)\mu} \cdot p^\mu_{\psi(2S)} = 0$, the matrix elements of the $B^0 \to \psi(2S)M^0$ is given by

$$\begin{aligned}\langle \psi(2S)M^0|H_{eff}|B^0\rangle \propto\ & \big[a_2 V_{cb} V^*_{cq'} - \big(a_3 + a_9 + r_\chi^{\psi(2S)}(a_5 + a_7)\big) V_{tb} V^*_{tq'}\big] \\ & \times f_{\psi(2S)} m_{\psi(2S)} F_1^{BM}(m^2_{\psi(2S)}) \big(\epsilon_{\psi(2S)} \cdot (p_B + p_M)\big),\end{aligned} \tag{5}$$

where $q' = d$ for π, $q' = s$ for K mesons and

$$\begin{aligned} r_\chi^{\psi(2S)} &= \frac{2m_{\psi(2S)}}{m_b} \frac{f^\perp_{\psi(2S)}}{f_{\psi(2S)}} \\ \epsilon_{\psi(2S)} \cdot (p_B + p_M) &= 2\epsilon_{\psi(2S)} \cdot p_B \\ &= \frac{2m_B}{m_{\psi(2S)}} |\overrightarrow{p}| \end{aligned} \tag{6}$$

where $|\overrightarrow{p}|$ is the absolute value of the 3-momentum of the π (or the K) in the B rest frame, and [4]

$$\begin{aligned} F_1^{BM}(q^2) &= \frac{F(0)}{1 - a_F(q^2/m_B^2) + b_F(q^2/m_B^2)^2}, \\ a_2^{(eff)} &= c_2^{(eff)} + \frac{c_1^{(eff)}}{N_c}, \\ a_{2n-1}^{(eff)} &= c_{2n-1}^{(eff)} + \frac{c_{2n}^{(eff)}}{N_c}, \qquad (n = 2, 3, 4, 5), \end{aligned} \tag{7}$$

$c_i^{(eff)}$ are the Wilson coefficients evaluated at the renormalization scale μ. These coefficients of the four-Fermi operators depend on the renormalization scale; in addition, in NLO precision, they also depend on the renormalization scheme. These unphysical dependences are compensated in principle by a corresponding scheme/scale dependence of the matrix elements of the operators. The renormalization group evolution from $\mu \simeq M_W$ to $\mu \simeq m_b$ has been evaluated in LO in the electromagnetic coupling and in the NLO precision in the strong coupling α_s [5]. I use c_i for the naive and c_i^{eff} for the QCD factorization approaches [6].
The corresponding simplified amplitudes are given by

$$\begin{aligned} A(B^0 \to \psi(2S)\pi^0) =\ & G_F m_{\psi(2S)} f_{\psi(2S)} (\epsilon_{\psi(2S)}.p_B) F_1^{B\pi}(m^2_{\psi(2S)}) \\ & \times \Big[a_2 V_{cb} V^*_{cd} - \big(a_3 + a_9 + r_\chi^{\psi(2S)}\big)(a_5 + a_7) V_{tb} V^*_{td}\Big], \\ A(B^0 \to \psi(2S)K^0) =\ & \sqrt{2} G_F m_{\psi(2S)} f_{\psi(2S)} (\epsilon_{\psi(2S)}.p_B) F_1^{BK}(m^2_{\psi(2S)}) \\ & \times \Big[a_2 V_{cb} V^*_{cs} - \big(a_3 + a_9 + r_\chi^{\psi(2S)}\big)(a_5 + a_7) V_{tb} V^*_{ts}\Big]. \end{aligned} \tag{8}$$

Note that if I change the spectator quarks of d with u in the Feynman diagrams of Figure 2, I can get the $B^+ \to \psi(2S)\pi^+$ and $B^+ \to \psi(2S)K^+$ decays. The decay amplitudes for the $B^+ \to \psi(2S)\pi^+$ can be obtained via $\sqrt{2}A(B^0 \to \psi(2S)\pi^0)$ and for the $B^+ \to \psi(2S)K^+$ is the same as $A(B^0 \to \psi(2S)K^0)$.

TABLE 1. Numerical Values of coefficients of a_i in the NDR scheme and leading and next to leading orders at the different scales.

		a_2	a_3	a_5	$a_7(10^{-3})$	$a_9(10^{-3})$
	$\mu = m_b/2$	0.008	0.004	-0.008	0.023	-0.945
LO	$\mu = m_b$	0.104	0.002	-0.003	0.067	-0.915
	$\mu = 2m_b$	0.177	0.001	-0.001	0.189	-0.890
	$\mu = m_b/2$	0.084	0.003	-0.012	0.062	-0.942
NLO	$\mu = m_b$	0.170	0.003	-0.005	0.070	-0.915
	$\mu = 2m_b$	0.235	0.002	-0.002	0.186	-0.890

NUMERICAL RESULTS FOR THE BRANCHING RATIOS

With the factorized decay amplitudes obtained in the previous section, it is ready to compute the decay rates given by [7]

$$\Gamma(B^0 \to \psi(2S)M^0) = \frac{p_c^3}{8\pi m_B^2}|A(B^0 \to \psi(2S)M^0)|^2, \tag{9}$$

with

$$p_c = \frac{1}{2m_B}\sqrt{\left(m_B^2 - (m_{\psi(2S)} + m_M)^2\right)}\sqrt{\left(m_B^2 - (m_{\psi(2S)} - m_M)^2\right)}. \tag{10}$$

The branching ratio can be achieved through

$$\text{BR}(B^0 \to \psi(2S)M^0) = \frac{\Gamma(B^0 \to \psi(2S)M^0)}{\Gamma_{\text{tot}}}. \tag{11}$$

To proceed with the numerical calculations, I need to specify the input parameters. For the CKM matrix elements, I use $V_{u_b} = 0.00127^{+0.00021}_{-0.00019} - \left(0.00325^{+0.00022}_{-0.00021}\right)i$, $V_{u_s} = 0.22534 \pm 0.00065$, $V_{ud} = 0.97427 \pm 0.00015$, $V_{c_b} = 0.0412^{+0.001}_{-0.0005}$ and $V_{c_s} = 0.97344 \pm 0.00016$, $V_{cd} = 0.22520 \pm 0.00065$, $V_{tb} = 0.999146^{+0.000021}_{-0.000046}$, $V_{ts} = 0.0404^{+0.0011}_{-0.0005}$, $V_{td} = 0.00867^{+0.00029}_{-0.00031}$ [8]. For $B \to K$ and $B \to \pi$ form factors, a good parametrization for the q^2 dependence can be given in terms of three parameters (see Equation (7)). I fix for $B \to K$ transition $F(0) = 0.374$, $a_F = 1.42$, $b_F = 0.434$ [4] and for $B \to \pi$ transition $F(0) = 0.25$, $a_F = 1.73$, $b_F = 0.95$ [9], namely, $F^{BK}(m^2_{\psi(2S)}) = 0.935$ and $F^{B\pi}(m^2_{\psi(2S)}) = 0.654$. The meson masses and decay constants needed in our calculations are (in units of MeV) $m_B = 5279.25 \pm 0.17$, $m_{\psi(2S)} = 3686.109 \pm 0.013$, $m_\pi = 139.57018 \pm 0.00035$, $m_K = 493.677 \pm 0.016$, $m_b = 4190 \pm 120$ [8]; $f_{\psi(2S)} = 282 \pm 14$, $f^\perp_{\psi(2S)} = 255 \pm 33$ [10, 11]; $G_F = 1.166 \times 10^{-5}$, $N_c = 3$, $\Gamma_{\text{tot}} = 4.219 \times 10^{-13}$GeV. The coefficients c_i have been calculated in different scheme and scales. In this paper I will use consistently the naive dimensional regularization (NDR) scheme and $\mu = m_b/2$, $\mu = m_b$ and $\mu = 2m_b$ scales. The values of a_i at the LO and NLO schemes are shown in table 1 [6]. Now I am able to calculate the branching ratios of the $B^{+(0)} \to \psi(2S)\pi^{+(0)}$ and $B^{+(0)} \to \psi(2S)K^{+(0)}$ decays by using the different values of μ which are shown in table 2. The experimental result for $\text{BR}(B^0 \to \psi(2S)\pi^0)$ which turns out to be $(1.17 \pm 0.17(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-4}$ [1] in very good agreement with my prediction.

CONCLUSION

In this research I have calculated the branching ratio of the $B^0 \to \psi(2S)\pi^0$ decay by using the factorization approach. I have obtained $\text{BR}(B^0 \to \psi(2S)\pi^0) = (1.067 \pm 0.059) \times 10^{-5}$ at the NLO scheme and $\mu = 2m_b$ scale. This decay mode, recently have reported by the Belle collaboration, they have obtained $\text{BR}\big(B^0 \to$

TABLE 2. Branching ratios of $B \to \psi(2S)\pi$ and $B \to \psi(2S)K$ decays

Decay mode	Schemes	$\mu = m_b/2$	$\mu = m_b$	$\mu = 2m_b$	Exp.[1, 8]
$BR(B^0 \to \psi(2S)\pi^0)$	LO	0.009 ± 0.000	0.235 ± 0.013	0.620 ± 0.035	1.17 ± 0.17
	NLO	0.188 ± 0.011	0.593 ± 0.033	1.067 ± 0.059	$(\times 10^{-5})$
$BR(B^+ \to \psi(2S)\pi^+)$	LO	0.018 ± 0.000	0.470 ± 0.026	1.240 ± 0.070	2.44 ± 0.30
	NLO	0.376 ± 0.022	1.186 ± 0.066	2.134 ± 0.118	$(\times 10^{-5})$
$BR(B^0 \to \psi(2S)K^0)$	LO	0.593 ± 0.032	1.405 ± 0.070	3.691 ± 0.184	6.20 ± 0.50
	NLO	1.142 ± 0.058	3.540 ± 0.177	6.344 ± 0.376	$(\times 10^{-4})$
$BR(B^+ \to \psi(2S)K^+)$	LO	0.593 ± 0.032	1.405 ± 0.070	3.691 ± 0.184	6.39 ± 0.33
	NLO	1.142 ± 0.058	3.540 ± 0.177	6.344 ± 0.376	$(\times 10^{-4})$

$\psi(2S)\pi^0\big) = \big(1.17 \pm 0.17(\text{stat}) \pm 0.08(\text{syst})\big) \times 10^{-5}$. My result is in good agreement with the Belle collaboration measurement. I have also calculated the same decays of $B^+ \to \psi(2S)\pi^+$, $B^0 \to \psi(2S)K^0$ and $B^+ \to \psi(2S)K^+$ in the framework of the naive and QCD factorization method and achieved $BR(B^+ \to \psi(2S)\pi^+) = (2.134 \pm 0.0.118) \times 10^{-5}$, $BR(B^0 \to \psi(2S)K^0) = (6.344 \pm 0.376) \times 10^{-4}$ and $BR(B^+ \to \psi(2S)K^+) = (6.344 \pm 0.376) \times 10^{-4}$. All results are in good agreement with the experimental results [8]. Since the CP-violating asymmetry for $B^0 \to \psi(2S)\pi^0$ decay is not available, the calculations of the last decays were considered for comparison with the main decay in the future.

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