Research Article

Measurement of the Quasi-Two-Body B Decays

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We study the contributions of the $B \rightarrow \psi(3770)K[\psi(3770) \rightarrow D\bar{D}]$, $B \rightarrow K^*(1410)\pi[K^*(1410) \rightarrow K\pi]$, and $B \rightarrow X(3872)K[X(3872) \rightarrow J/\psi\gamma, \psi(2S)\gamma, D\bar{D}\pi, J/\psi\omega, J/\psi\pi\pi, \text{ and } D\bar{D}^*\pi]$ quasi-two-body decays. There are no existing previous measurements of the three-body branching fractions for three final states of the $X(3872) \rightarrow J/\psi\gamma, \psi(2S)\gamma$, and $D\bar{D}\pi$, but several quasi-two-body modes that can decay to this final state have been seen.

1. Introduction

The three-body mesondecays are generally dominated by intermediate vector and scalar resonances; this means that there are a resonance state and a pseudoscalar meson which they proceed by quasi-two-body decays [1–4]. In fact, analysis of three-body B decays using the Dalitz plot technique leads us to the many quasi-two B decays [1]. The study of the $B \rightarrow \psi(3770)K$, $B \rightarrow K^*(1410)\pi$, and $B \rightarrow X(3872)K$ via quasi-two-body decays was considered. These include $B^+ \rightarrow \psi(3770)K^+$ and $B^0 \rightarrow \psi(3770)K^0$, observed in the $\psi(3770) \rightarrow D^0\bar{D}^0$ channel and also seen in $\psi(3770) \rightarrow D^+D^-$; $B^0 \rightarrow K^*(1410)^+\pi^-$, seen in $K^*(1410)^+ \rightarrow K^0\pi^+$; $B^+ \rightarrow X(3872)K^+$ and $B^0 \rightarrow X(3872)K^0$, seen in $X(3872) \rightarrow J/\psi\pi^+\pi^-$, $J/\psi\omega$ and $\bar{D}^{*0}D^0K^0$ channel [5]. The decays $B^+ \rightarrow X(3872)K^+$ and $B^0 \rightarrow X(3872)K^0$ have also been observed with $X(3872) \rightarrow J/\psi\gamma, \psi(2S)\gamma$, and $D^0\bar{D}^0\pi^0$ [5]. In this paper, we do not perform a Dalitz plot analysis but instead use information on intermediate modes including narrow resonances by studying the two-body invariant mass distributions, because there are no existing previous measurement branching fractions for some of the three-body decays such as $X(3872) \rightarrow J/\psi\gamma, \psi(2S)\gamma$, and $D^0\bar{D}^0\pi^0$, but quasi-two-body modes that can decay to these final states have been seen. Hence, we present the results of a search for the three-body decay including short-lived intermediate two-body modes that can decay to these final states.

In general factorization approach, to obtain the amplitudes of the two-body decays, the Feynman quark diagrams should be plotted, and quasi-two-body decays of the heavy mesons can be also expressed in terms of some quark-graph amplitudes. For example we take $B^0 \rightarrow K^*(1410)^+\pi^-$ as an illustration. Under the factorization approach, its decay amplitude consists of three distinct factorizable terms: (i) the current-current process through the tree $b \rightarrow u$ transition, (ii) the transition process induced by $b \rightarrow s$ penguins, and (iii) the annihilation process. Note that weak-annihilation contributions are too small, so we ignore them in our calculations.

2. Quasi-Two-Body Decay Amplitudes

It is known that in the narrow width approximation, in the models we use to obtain the amplitudes of the decays, the 3-body decay rate obeys the factorization relation [3]

$$\begin{aligned} \text{Br}(B \rightarrow RM \rightarrow M_1M_2M) \\ = \text{Br}(B \rightarrow RM) \times \text{Br}(R \rightarrow M_1M_2), \end{aligned} \quad (1)$$

with R being a vector meson resonance and M, M_1 , and M_2 are pseudoscalar and vector final state mesons. The intermediate vector meson contributions to three-body decays are identified through the vector current, and their effects are described in terms of the Breit-Wigner formalism. The Breit-Wigner resonant term associated to quasi-two-body $R + M$

FIGURE 1: Quark diagrams illustration of the processes of the $B^{+(0)} \rightarrow \psi K^{+(0)}$ and $XK^{+(0)}$ decays.

FIGURE 2: Quark diagrams illustration of the process of the $B^0 \rightarrow K^{*+} \pi^-$ decay.

state which seems to play an important role as indicated by experiments. We have to calculate the branching ratios of the $\text{Br}(B \rightarrow RM)$ by using the Feynman quark diagrams and using the experimental information for the $\text{Br}(R \rightarrow M_1 M_2)$ decays as follows [5]:

$$\begin{aligned}
 \text{Br}(\psi(3770) \rightarrow D^0 \bar{D}^0) &= (52 \pm 5) \%, \\
 \text{Br}(\psi(3770) \rightarrow D^+ D^-) &= (41 \pm 4) \%, \\
 \text{Br}(K^*(1410)^+ \rightarrow K^0 \pi^+) &= (6.6 \pm 1.3) \%, \\
 \text{Br}\left(X(3872) \rightarrow \frac{J}{\psi \pi^+ \pi^-}\right) &> 2.6\%, \\
 \text{Br}\left(X(3872) \rightarrow \frac{J}{\psi \omega}\right) &> 1.9\%, \\
 \text{Br}\left(X(3872) \rightarrow \frac{J}{\psi \gamma}\right) &> 9 \times 10^{-3}, \\
 \text{Br}(X(3872) \rightarrow D^0 \bar{D}^0 \pi^0) &> 3.2 \times 10^{-3}, \\
 \text{Br}(X(3872) \rightarrow \bar{D}^0 D^0) &> 5 \times 10^{-3}, \\
 \text{Br}(X(3872) \rightarrow \psi(2S) \gamma) &> 3.0\%.
 \end{aligned} \tag{2}$$

We calculate the branching ratios of the intermediate states two-body decays. Feynman diagrams related to these decays are shown in Figures 1 and 2.

A detailed discussion of the QCD factorization (QCDF) approach can be found in [6–9]. Factorization is a property of the heavy-quark limit, in which we assume that the b quark

mass is parametrically large. The QCDF formalism allows us to compute systematically the matrix elements of the effective weak Hamiltonian in the heavy-quark limit for certain two-body final states $\psi K^{+(0)}$, $XK^{+(0)}$, and $K^{*+} \pi^-$. In this section, we obtain the amplitude of $B^{+(0)} \rightarrow \psi K^{+(0)}$, $B^{+(0)} \rightarrow XK^{+(0)}$, and $B^0 \rightarrow K^{*+} \pi^-$ decays by using the QCDF method. We adopt leading order Wilson coefficients at the scale m_b for QCDF approach. According to the QCDF, the amplitudes of the $B^{+(0)} \rightarrow \psi K^{+(0)}$, $B^{+(0)} \rightarrow XK^{+(0)}$, and $B^0 \rightarrow K^{*+} \pi^-$ decays are given by

$$\begin{aligned}
 A(B^{+(0)} \rightarrow \psi(3770) K^{+(0)}) &= \sqrt{2} G_F m_\psi f_\psi (\epsilon_\psi \cdot p_B) F_1^{BK}(m_\psi^2) \\
 &\quad \times (a_2 V_{cb} V_{cs}^* + a_3 \lambda_p),
 \end{aligned} \tag{3}$$

$$\begin{aligned}
 A(B^{+(0)} \rightarrow X(3872) K^{+(0)}) &= \sqrt{2} G_F m_X f_X (\epsilon_X \cdot p_B) F_1^{BK}(m_X^2) \\
 &\quad \times (a_2 V_{cb} V_{cs}^* + a_3 \lambda_p),
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 A(B^0 \rightarrow K^*(1410)^+ \pi^-) &= \sqrt{2} G_F m_{K^*} f_{K^*} (\epsilon_{K^*} \cdot p_B) F_1^{B\pi}(m_{K^*}^2) \\
 &\quad \times [(a_1 + a_2) V_{ub} V_{us}^* + a_4 \lambda_p],
 \end{aligned} \tag{5}$$

TABLE 1: Wilson coefficients c_i in the NDR scheme at the leading order and next to leading order.

	c_1	c_2	c_3	c_4
NLO	1.081	-0.190	0.014	-0.036
LO	1.117	-0.268	0.012	-0.027

TABLE 2: Numerical values of effective coefficients a_i for $\bar{b} \rightarrow \bar{s}$ transition at the leading and next to leading order and $N_c = 3$.

	a_1	a_2	a_3	a_4
NLO	1.02	0.17	0.003	-0.02
LO	1.03	0.11	0.002	-0.03

where

$$\epsilon_V \cdot p_B = \frac{m_B}{m_V} |\vec{p}_V|, \quad (V = \psi, X, K^*),$$

$$\lambda_p = \sum_{p=u,c} V_{pb} V_{ps}^*,$$

$$F_1^{BP}(q^2) = \frac{F(0)}{1 - a_F(q^2/m_B^2) + b_F(q^2/(m_B^2))^2}, \quad (P = K, \pi), \quad (6)$$

where $|\vec{p}_V| = \sqrt{(p_V^0)^2 - (m_V)^2}$ is the absolute value of the 3-momentum of the vector meson in the B rest frame.

3. Numerical Results

To proceed with the numerical calculations, we need to specify the input parameters. For the CKM matrix elements, we use $V_{ub} = 0.00351_{-0.00014}^{+0.00015}$, $V_{us} = 0.22534 \pm 0.00065$, $V_{cb} = 0.0412_{-0.0005}^{+0.001}$, and $V_{cs} = 0.97344 \pm 0.00016$ [5]. For $B \rightarrow K$ and $B \rightarrow \pi$ form factors, a good parametrization for the q^2 dependence can be given in terms of three parameters (see (6)). We fix for $B \rightarrow K$ transition $F(0) = 0.374$, $a_F = 1.42$, $b_F = 0.434$ [10] and for $B \rightarrow \pi$ transition $F(0) = 0.25$, $a_F = 1.73$, $b_F = 0.95$ [11], namely, $F^{BK}(m_\psi^2) = 0.962$, $F^{BK}(m_X^2) = 1.283$, and $F^{B\pi}(m_{K^*(1410)}^2) = 0.284$. The meson masses and decay constants needed in our calculations are (in units of MeV) $m_B = 5279.25 \pm 0.17$, $m_\psi = 3772.15 \pm 0.33$, $m_X = 3871.68 \pm 0.17$, $m_{K^*(1410)} = 1414 \pm 15$ [5]; $f_\psi = 384 \pm 14$ [12]; $f_X = 446 \pm 16$ [13]. The Wilson coefficients c_i have been calculated in different schemes. In this paper we will use consistently the naive dimensional regularization (NDR) scheme. The values of c_i at the scale $\mu = m_b$ at the leading order (LO) and next to leading order (NLO) are shown in Table 1 [9, 14]. Numerical values of effective coefficients a_i for $\bar{b} \rightarrow \bar{s}$ transition at $N_c = 3$ are shown in Table 2. According to Table 2, it is not much difference between effective coefficients a_i at the LO and NLO; therefore, we use them at the LO: $a_1 = 1.03$, $a_2 = 0.11$, $a_3 = 0.002$, and $a_4 = -0.03$ [9, 14].

TABLE 3: Branching ratios of quasi-two-body decays obtained from the studies of three-body decays based on the factorization approach.

	Decay mode	Theory	Exp. [5]	Units
$\psi(3770)K^+$;	$\psi \rightarrow D^0 \bar{D}^0$	1.56 ± 0.32	1.6 ± 0.4	$\times 10^{-4}$
	$\psi \rightarrow D^+ D^-$	12.28 ± 2.61	9.4 ± 3.5	$\times 10^{-5}$
$\psi(3770)K^0$;	$\psi \rightarrow D^0 \bar{D}^0$	1.56 ± 0.32	<1.23	$\times 10^{-4}$
	$\psi \rightarrow D^+ D^-$	1.23 ± 0.26	<1.88	$\times 10^{-4}$
$X(3872)K^+$;	$X \rightarrow J/\psi \pi^+ \pi^-$	>9.17	8.6 ± 0.8	$\times 10^{-6}$
	$X \rightarrow J/\psi \gamma$	>3.20	2.1 ± 0.4	$\times 10^{-6}$
	$X \rightarrow \psi(2S) \gamma$	>10.59	4 ± 4	$\times 10^{-6}$
	$X \rightarrow D^0 \bar{D}^0 \pi^0$	>0.016	1.0 ± 0.4	$\times 10^{-4}$
	$X \rightarrow \bar{D}^{0*} D^0$	>0.20	8.5 ± 2.6	$\times 10^{-5}$
	$X \rightarrow J/\psi \pi^+ \pi^-$	>9.17	4.3 ± 1.3	$\times 10^{-6}$
$X(3872)K^0$;	$X \rightarrow J/\psi \gamma$	>3.20	<2.41	$\times 10^{-6}$
	$X \rightarrow \psi(2S) \gamma$	>1.06	<6.61	$\times 10^{-6}$
	$X \rightarrow D^0 \bar{D}^0 \pi^0$	>0.016	1.7 ± 0.8	$\times 10^{-4}$
	$X \rightarrow \bar{D}^{0*} D^0$	>0.20	1.2 ± 0.4	$\times 10^{-4}$
	$X \rightarrow J/\psi \omega$	>6.72	6.0 ± 3.2	$\times 10^{-6}$
	$X \rightarrow J/\psi \pi^+ \pi^-$	>9.17	4.3 ± 1.3	$\times 10^{-6}$
$K^*(1410)^+ \pi^-; K^* \rightarrow K^0 \pi^+$		2.53 ± 0.21	<3.8	$\times 10^{-6}$

Now we are able to calculate the branching ratios of the $B^{+(0)} \rightarrow \psi(3770)K^{+(0)}$, $B^{+(0)} \rightarrow X(3872)K^{+(0)}$ and $B^0 \rightarrow K^*(1410)^+ \pi^-$ decays by using (3)–(5) as follows

$$\text{Br}(B^{+(0)} \rightarrow \psi(3770)K^{+(0)}) = (2.95_{-0.86}^{+1.10}) \times 10^{-4},$$

$$\text{Br}(B^{+(0)} \rightarrow X(3872)K^{+(0)}) = (3.12_{-0.85}^{+1.00}) \times 10^{-4}, \quad (7)$$

$$\text{Br}(B^0 \rightarrow K^*(1410)^+ \pi^-) = (2.57_{-0.52}^{+0.58}) \times 10^{-5}.$$

The experimental result for $\text{Br}(B \rightarrow \psi(3770)K)$ which turns out to be $(4.9 \pm 1.3) \times 10^{-4}$ [5] is in very good agreement with our prediction. As we know the branching ratio of $B \rightarrow X(3872)K$ decay has already been estimated: (a) in [15] they have used QCD sum rules to calculate the branching ratio and predicted $(0.38 \pm 0.06) \times 10^{-6}$, (b) in [16] they have analyzed the decay $B \rightarrow XK$ and the decays of B into $D^0 \bar{D}^0 K$ and $D^{0*} \bar{D}^0 K$ near the threshold for the charm mesons by separating the decay amplitudes into short-distance factors and long-distance factors, and they have predicted for branching ratio 2.9×10^{-5} , while the experimental result of this decay is $\text{Br}(B \rightarrow \psi(3770)K) < 3.2 \times 10^{-4}$ [17]. By using (1), (2), and (7) the branching ratios of quasi-two-body decays are summarized in Table 3. Note that the experimental BRs for $X(3872)$ decay modes (see (2)) only have lower bounds, so the theory predictions involving these modes in Table 3 only have lower bounds.

4. Conclusion

In this research we have calculated the branching ratios of the $B \rightarrow \psi(3770)K[\psi(3770) \rightarrow D\bar{D}]$, $B \rightarrow K^*(1410)\pi[K^*(1410) \rightarrow K\pi]$, and $B \rightarrow X(3872)K[X(3872) \rightarrow J/\psi\gamma, \psi(2S)\gamma, D\bar{D}\pi, J/\psi\omega, J/\psi\pi\pi \text{ and } D\bar{D}^*\pi]$ decays in the

framework of the quasi-two-body method. We have also measured the branching ratios of two-body decays including the short-lived intermediate mesons by using the QCDF method. Our calculation results are shown in Table 3. There are no existing previous measurement branching fractions for some of the three-body decays such as $B \rightarrow J/\psi\gamma K$, $\psi(2S)\gamma K$, and $D\bar{D}\pi K$, but quasi-two-body modes that can decay to these final states have been seen.

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