W-exchange and W-annihilation processes of B mesons

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Abstract

Using the PQCD method we calculate the W-exchange and the W-annihilation processes of B mesons, which in general involve a charm quark or anti-quark in the final state. The nonvanishing amplitudes of these processes are found to be suppressed by a factor of \(m_c/m_b\) compared to the tree or the time-like penguin processes, but some of them are within the reach of observation at the future B-factories, and \(\bar{B}_d^0 \rightarrow D_\pm K^-\) whose branching ratio is found to be \(6.6 \times 10^{-6}\) can be found even before the B-factory era. Comparisons with the results based on the BSW model are also given.

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In the forthcoming years, more data of B decay processes will be available at Tevatron, CLEO and at the B-factories. Rare hadronic B decays dominated by the W-exchange or the W-annihilation diagrams with the branching ratios of $10^{-7}$ or $10^{-8}$ are possible to be measured, bringing the necessity of estimating these kinds of processes in advance. In the past, most of the theoretical investigations on the nonleptonic processes are based on the BSW model, where the factorization hypothesis has been used together with some phenomenological inputs such as $a_1$ and $a_2$. While the usefulness of the factorization hypothesis in these rare decays is doubtful, it is also not certain that these phenomenological inputs are independent of the processes; that is to say, using the parameters $a_1$ and $a_2$ extracted from one experiment to other processes cannot be taken for granted.

In the present study, we focus on the rare B decay processes driven by the W-exchange or the W-annihilation diagrams. Some of these processes have been calculated recently within the BSW model where very small branching ratios have been claimed. Here we want to use the perturbative QCD (PQCD) method to re-analyse them and compare the results given by these two methods. We follow directly Ref. which takes the PQCD method as a phenomenologically acceptable model. For instance, reasonable agreements have been arrived in the observed modes $B \to K^*\gamma$ and $B \to KJ/\psi$. In the present study of the W-exchange and the W-annihilation processes, we leave the applicability of this method as an open question for the moment, and will return to this issue at the very end.

We denote the processes at the hadronic level as $\bar{B}_\delta (b\bar{\delta}) \to Y (\alpha\gamma) + Z (\gamma\beta) \ (\gamma = u, d, s)$. Their momenta are denoted by $P_B$, $P_Y$ and $P_Z$, and masses by $M_B$, $M_Y$ and $M_Z$, respectively. The effective Hamiltonian for these processes is

$$H_{eff} = 4 \frac{G_F}{\sqrt{2}} V_{ckm} (C'_1(\mu)O_1 + C'_2(\mu)O_2),$$

where the CKM factor is defined as

$$V_{ckm} = \begin{cases} V_{\delta\beta}V_{\alpha\alpha}^* & \text{for W-annihilation process,} \\ V_{\alpha\beta}V_{\delta\delta}^* & \text{for W-exchange process,} \end{cases}$$

the effective four-quark operators are

$$O_1 = (\bar{\delta}\gamma_\mu P_L\beta)(\bar{\alpha}\gamma_\mu P_Lb),$$
$$O_2 = (\bar{\alpha}\gamma_\mu P_L\beta)(\bar{\delta}\gamma_\mu P_Lb),$$

$P_L = (1 - \gamma_5)/2$. $\alpha, \beta = u$ or $c$, $\delta = d$ or $s$ for the W-exchange processes, and $\beta, \delta = u$ or $c$, $\alpha = d$ or $s$ for the W-annihilation processes, and the Wilson coefficients are

$$C'_1 = C_1 \ , \ C'_2 = C_2 \text{ for W-exchange process,}$$
$$C'_1 = C_2 \ , \ C'_2 = C_1 \text{ for W-annihilation process.}$$
Calculation the Wilson coefficients at $\mu = 5\text{GeV}$ gives $C_1 = 1.10, \quad C_2 = -0.235$.

Following the PQCD method[6], the figures which are relevant to the W-exchange or W-annihilation processes are depicted in Fig 1. We take the interpolating fields in the standard ways as[4, 5, 6]

$$\psi_B = \frac{1}{\sqrt{2}} \frac{I_c}{\sqrt{3}} \phi_B(x) \gamma_5 (P_B - M_B),$$  \hspace{1cm} (5)

$$\psi_Y = \frac{1}{\sqrt{2}} \frac{I_c}{\sqrt{3}} \phi_Y(y) \gamma_5 (P_Y + M_Y),$$  \hspace{1cm} (6)

$$\psi_Z = \frac{1}{\sqrt{2}} \frac{I_c}{\sqrt{3}} \phi_Z(z) \gamma_5 (P_Z + M_Z).$$  \hspace{1cm} (7)

Here $I_c$ is an identity in the color space.

The momentum fractions carried by every quark lines are labeled in Fig 1 in an obvious way. The momentum flows for the gluon and for the quark lines are

$$l_g = P_Y y_1 + P_Z z_2, q_b = P_B x_2 - l_g, q_6 = -(P_B x_1 - l_g), q_\alpha = P_Y y_2 + l_g, q_\beta = -(P_Z z_1 + l_g).$$  \hspace{1cm} (8)

To present the results in a concise way, we also denote

$$D_g \equiv l_g^2 = M_Y^2 y_1^2 + M_Z^2 z_2^2 + (M_B^2 - M_Y^2 - M_Z^2) y_1 z_2,$$

$$D_b \equiv q_b^2 = M_Y^2 y_1^2 + M_Z^2 z_2^2 - (M_B^2 + M_Y^2 - M_Z^2) x_2 y_1 - (M_B^2 - M_Y^2 - M_Z^2) y_1 z_2,$$

$$D_\delta \equiv q_6^2 - m_6^2 = M_Y^2 y_1^2 + M_Z^2 z_2^2 + M_B^2 x_1^2 - (M_B^2 + M_Y^2 - M_Z^2) x_1 y_1 - (M_B^2 - M_Y^2 - M_Z^2) y_1 z_2 - m_6^2,$$

$$D_\alpha \equiv q_\alpha^2 - m_\alpha^2 = M_Y^2 y_1^2 + M_Z^2 z_2^2 + (M_B^2 - M_Y^2 - M_Z^2) z_2 - m_\alpha^2,$$

$$D_\beta \equiv q_\beta^2 - m_\beta^2 = M_Y^2 y_1^2 + (M_B^2 - M_Y^2 - M_Z^2) y_1 - m_\beta^2.$$  \hspace{1cm} (9)

Now we are in the position of calculating the decay amplitudes. First, we take the W-exchange diagram as an example. The decay amplitudes are calculated from Fig 1 (a) to Fig 1 (d). With the insertion of the operator $O_1 = (\bar{\delta} \gamma_\mu P_L \beta)(\bar{\alpha} \gamma_\mu P_L b)$, the calculations of the four diagrams give:

$$A^1_a = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Y \gamma^\mu P_L (q_b + m_b) \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Z \gamma^\mu P_L \right] - \frac{i}{D_b D_g},$$

$$A^1_b = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) (q_6 + m_6) \gamma_\mu P_L \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Y \gamma^\mu P_L \right] - \frac{i}{D_b D_g},$$

$$A^1_c = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Y \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) (q_\alpha + m_\alpha) \gamma_\mu P_L \right] - \frac{i}{D_b D_g},$$

$$A^1_d = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L (q_\beta + m_\beta) \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_s \right) \psi_Y \gamma^\mu P_L \right] - \frac{i}{D_b D_g}.$$

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where \([dx], [dy], \text{and } [dz]\) denote \((dx_1dx_2), (dy_1dy_2)\) and \((dz_1dz_2)\), respectively. With the insertion of the operator \(O_2 = (\bar{c} \gamma_\mu P_L \beta)(\bar{d} \gamma_\mu P_L b)\), the results are:

\[
\mathcal{A}_a^2 = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L (\varphi_0 + m_b) \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) \right] \text{Tr} \left[ \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) \psi_Y \gamma^\mu P_L \right] \frac{i}{D_{bD_g}},
\]
\[
\mathcal{A}_b^2 = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) (\varphi_0 + m_b) \gamma_\mu P_L \right] \text{Tr} \left[ \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) \psi_Y \gamma^\mu P_L \right] \frac{i}{D_{sD_g}},
\]
\[
\mathcal{A}_c^2 = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L \right] \text{Tr} \left[ \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) \psi_Y \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) (\varphi_0 + m_c) \gamma^\mu P_L \right] \frac{i}{D_{aD_g}},
\]
\[
\mathcal{A}_d^2 = \int_0^1 [dx][dy][dz] \text{Tr} \left[ \psi_B \gamma_\mu P_L \right] \text{Tr} \left[ \psi_Z \left( i \frac{\lambda^a}{2} \gamma_\alpha g_\alpha \right) \psi_Y \gamma^\mu P_L (\varphi_0 + m_\beta) \right] \frac{i}{D_{D_g}}.
\]

Performing the trace operation in both the spinor and the color space, we find that the contributions of \(\mathcal{A}_a^2, \mathcal{A}_b^2\) vanish due to their color structures, thus:

\[
\mathcal{A}_a^1 = -\frac{8}{3\sqrt{6}} g_s^2 \int_0^1 [dx][dy][dz] \Psi(x, y, z) \left[ P_{BY}(P_BZx_2 - P_{YZ}y_1 - 2M_Z^2z_2) - M_B^2P_{YZ}x_2 \right] \frac{1}{D_{bD_g}},
\]
\[
\mathcal{A}_b^1 = -\frac{8}{3\sqrt{6}} g_s^2 \int_0^1 [dx][dy][dz] \Psi(x, y, z) \left[ P_{BZ}(P_{YZ}z_2 - P_{BY}x_1 + 2M_Y^2y_1) + M_Bm_\delta P_{YZ} \right] \frac{1}{D_{sD_g}},
\]
\[
\mathcal{A}_c^1 = -\frac{8}{3\sqrt{6}} g_s^2 \int_0^1 [dx][dy][dz] \Psi(x, y, z) \left[ P_{BY}M_Z^2z_2 - P_{BZ}(M_Y^2 + P_{YZ}z_2) \right]
\[+m_\alpha(M_ZP_{BY} + 2MYP_{BZ})] \frac{1}{D_{aD_g}},
\]
\[
\mathcal{A}_d^1 = -\frac{8}{3\sqrt{6}} g_s^2 \int_0^1 [dx][dy][dz] \Psi(x, y, z) \left[ P_{BY}(P_{YZ}y_1 + M_Y^2) - P_{BZ}M_Y^2y_1 \right]
\[-m_\beta(2M_ZP_{BY} + MYP_{BZ})] \frac{1}{D_{D_g}},
\]
\[
\mathcal{A}_a^2 = 0, \quad \mathcal{A}_b^2 = 0, \quad \mathcal{A}_c^2 = 3A_c^1, \quad \mathcal{A}_d^2 = 3A_d^1,
\]

where \(\Psi(x, y, z) = \phi_B(x)\phi_Y(y)\phi_Z(z)\) and \(P_{ij} = 2P_i \cdot P_j\). We have set \(M_YM_Z = 0\) since there are light mesons in the final states.

Using the effective Hamiltonian (1) for \(\bar{B}_s(b\bar{d}) \rightarrow Y(\alpha\bar{\gamma}) + Z(\gamma\bar{\beta})\) decays, then the decay amplitude can be written as

\[
A = \frac{4G_F}{\sqrt{2}} V_{ckm} \left[ C'_1(A_d^1 + A_d^1) + (C'_1 + 3C'_2)(A_c^1 + A_d^1) \right]
\]

The W-exchange processes can be divided into two cases: one is \(\alpha = u\) and \(\beta = c\), the other is \(\alpha = c\) and \(\beta = u\). Three processes belonging to the former, they are \(\mathcal{B}_d^0 \rightarrow D_s^-K^+, \mathcal{B}_s^0 \rightarrow D^-\pi^+\) and \(\mathcal{B}_s^0 \rightarrow \bar{D}^0\pi^0\). In this case, because the \(Y\) meson is a light meson, we set \(M_Y = 0\). The decay amplitudes can be simplified as

\[
A_a^1 = -\frac{8}{3\sqrt{6}} g_s^2 \int_0^1 [dx][dy][dz] \Psi(x, y, z) \frac{1}{z_2 (y_1 + \frac{\Delta z}{1 - \Delta z})} \left[ y_1 - \frac{\Delta z}{(x_2 - z_2)y_1 + (1 + \Delta z)(x_2z_2 - \Delta z^2)} \right]
\]

4
where $\Delta Z = m_2^2/M_B^2$.

The later case of $\alpha = c$ and $\beta = u$ also has three corresponding processes which are $\bar{B}_d^0 \rightarrow D^*_s K^-$, $\bar{B}_s^0 \rightarrow D^* \pi^-$ and $\bar{B}_s^0 \rightarrow D^0 \pi^0$. Again the light meson mass $M_Z = 0$, and the decay amplitudes are simplified into

$$A_b^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (y_1 - \frac{\Delta y y_1}{1 - \Delta Y})(y_2 + \frac{\Delta y y_1}{1 - \Delta Y}) 1 - \Delta Y},$$

$$A_c^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (1 - \Delta Z + \Delta z y_2)(y_1 - \frac{\Delta z y_2}{1 - \Delta Z}) 1 - \Delta Z},$$

$$A_d^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (y_1 - \frac{\Delta z y_2}{1 - \Delta Z})(y_2 + \frac{\Delta z y_2}{1 - \Delta Z}) 1 - \Delta Z},$$

where $\Delta Y = M_Y^2/M_B^2$.

Next, we turn to the pure W-annihilation processes which differ from the W-exchange processes in the CKM factor and the Wilson coefficients as described in Eq. (2) and Eq. (4), respectively. There are also two cases for the pure annihilation processes: one is $\delta = u$ and the other is $\delta = c$, corresponding to the W-annihilation processes of $B_u^-$ into a $D$ meson plus a light one, and of $B_c^-$ into two light mesons, respectively. The analyses of the later case of $B_c^-$ processes need more likely to be performed within the potential model [5], which is beyond the present investigation. In the former case, we have

$$A_a^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (y_1 - \frac{\Delta z y_2}{1 - \Delta Z})(y_2 + \frac{\Delta z y_2}{1 - \Delta Z}) 1 - \Delta Z},$$

$$A_b^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (1 - \frac{\Delta y y_1 y_2}{1 - \Delta Y})(y_2 + \frac{\Delta y y_1 y_2}{1 - \Delta Y}) 1 - \Delta Y},$$

$$A_c^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (1 - \Delta Z + \Delta z y_2)(y_1 - \frac{\Delta z y_2}{1 - \Delta Z}) 1 - \Delta Z},$$

$$A_d^1 = -\frac{8}{3\sqrt{6}} g_2^2 \int_0^1 [dx][dy][dz] \Psi(x,y,z) \frac{1}{y_2 (y_1 - \frac{\Delta z y_2}{1 - \Delta Z})(y_2 + \frac{\Delta z y_2}{1 - \Delta Z}) 1 - \Delta Z},$$

where $\Delta Z = m_2^2/M_B^2$.
To get the numerical estimations, we choose the wavefunctions for the mesons as

\begin{align*}
\phi_B(x) &= \frac{f_B}{2\sqrt{3}}\delta(x - \epsilon_B), \\
\phi_D(x) &= \frac{f_D}{2\sqrt{3}}\delta(x - \epsilon_D), \\
\phi_K(x) &= \sqrt{3}f_Kx(1-x), \\
\phi_\pi(x) &= \sqrt{3}f_\pi x(1-x).
\end{align*}

(17)

We will take in the numerical calculations \(\epsilon_B = 0.07, \epsilon_{B_s} = 0.09, \epsilon_D = 0.2\) and \(\epsilon_{D_s} = 0.25\). Under these choices, all the nonvanishing decay amplitudes considered here are proportional to \(1/\epsilon_{D(s)}\). This observation is a common feature of the peak approximations of the wavefunctions for the heavy mesons, independent of the choices of the wavefunctions for the light mesons. Note that from the previous studies, the amplitudes for the tree diagrams and for the time-like penguins are proportional to \(1/\epsilon_B\) \([6]\), while there is no such enhancement in the amplitudes for the space-like penguins \([9]\). Here what we find is that the amplitudes for the pure W-exchange or the W-annihilation processes, which in general involve \(D\) or \(\bar{D}\) mesons in the final states, are suppressed by a factor of \(\epsilon_B/\epsilon_D \sim m_c/m_b \sim 1/3\) compared to the tree or time-like penguin amplitudes. The reason for these results can be understood using the same arguments which induce the helicity suppression mechanism \([10]\), as has been supposed in the quark diagram scheme in \([11]\).

To compare with the results given by \([3]\), we adopt the same numerical values for the CKM matrix elements, for the mass parameters and for the decay constants \([1]\) as those used in \([3]\). Our results are presented in Table 1.

It can be observed from Table 1 that, except the double CKM suppressed process \(B^- \to D_s^-K^0\), all these W-exchange and W-annihilation processes are within the reach of discovery at the future B-factories \([4]\), since our results are in general larger than the predictions made within the BSW model \([3]\). Among them, the process \(\bar{B}_d^0 \to D_s^+K^-\) whose branching ratio is found here to be \(6.6 \times 10^{-6}\), might be discovered even before the B-factory era based on our predictions.

Now we discuss the applicability of the PQCD method in the W-exchange and W-annihilation processes we have focused on. In \([3]\) lower cuts on the integrations over the momentum fractions have been enforced to avoid all possible poles; consequently, the numbers given in \([3]\) are of orders smaller than those given in the BSW model \([3]\). Different from \([3]\), in \([5]\) no cut has been required and some numbers are comparable with the data. In our case, there exists only the

\[\text{Note that our definitions of the decay constants differ from those in [3] by a factor of } 1/\sqrt{2}.\]

\[\text{At the designed SLAC B-factory, } 3 \times 10^8 \text{ pairs of } B_s\bar{B}_s \text{ and more non-strange B meson pairs can be produced[12].}\]
\( \delta \) pole (see Figure 1(b)); all other poles, especially the gluonic pole, lie out of the range \([0,1]\) of the integration. A safe lower cut to avoid this \( \delta \) pole in all these channels is 0.1 for the momentum fraction of the light meson. We also give our predictions in Table 1 based on this cut. Comparing to those without the cut, it can be seen that the branching ratios are reduced by 20\% to 60\%. These changes are quite moderate to justify the method, if comparisons with the processes considered in [6] are made.

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| Process                        | Ref. [3] | This work\textsuperscript{a} | This work\textsuperscript{b} |
|-------------------------------|----------|-------------------------------|-------------------------------|
| $B^- \to D^- \bar{K}^0$       | 8.1 $\times 10^{-9}$  | 1.0 $\times 10^{-8}$  | 4.9 $\times 10^{-9}$  |
| $B^- \to D_s^- \bar{K}^0$    | 4.2 $\times 10^{-10}$ | 5.5 $\times 10^{-10}$ | 5.1 $\times 10^{-10}$ |
| $B_d^0 \to D_s^+ \bar{K}^-$  | 6.5 $\times 10^{-8}$  | 6.6 $\times 10^{-6}$  | 4.7 $\times 10^{-6}$  |
| $\bar{B}_d^0 \to D_s^- \bar{K}^+$ | 2.1 $\times 10^{-11}$ | 3.5 $\times 10^{-9}$  | 1.2 $\times 10^{-9}$  |
| $B_s^0 \to D^+ \pi^-$        | 1.2 $\times 10^{-8}$  | 5.8 $\times 10^{-7}$  | 4.7 $\times 10^{-7}$  |
| $\bar{B}_s^0 \to D^0 \pi^0$  | 1.2 $\times 10^{-8}$  | 2.9 $\times 10^{-7}$  | 2.3 $\times 10^{-7}$  |
| $\bar{B}_s^0 \to D^- \pi^+$  | 1.5 $\times 10^{-9}$  | 4.9 $\times 10^{-8}$  | 3.2 $\times 10^{-8}$  |
| $\tilde{B}_s^0 \to \bar{D}^0 \pi^0$ | 1.5 $\times 10^{-9}$  | 2.5 $\times 10^{-8}$  | 1.6 $\times 10^{-8}$  |

**Table 1.** Comparison of the results with those of [3].

\textsuperscript{a}: no cut enforced; \textsuperscript{b}: lower cut at 0.1.

**Figure 1.** Diagrams which are relevant in PQCD calculations of the W-exchange and the W-annihilation processes. The solid blob denotes an insertion of the four-quark operator $O_1$ or $O_2$. Momentum fractions are labelled as $x$, $1-x$, etc.
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