Non-Spectator Contributions to Inclusive Charmless $B$ Decays

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Abstract

The light quarks inside $B$ mesons are usually treated as spectators and do not affect the decay rates which are assumed to be purely due to $b$ quark decays. In this paper we calculate the non-spectator contributions to inclusive charmless $B$ decays due to the spectator effects. We find that the non-spectator contributions to the branching ratio for $\bar{B}^0$ are small ($< 2 \times 10^{-4}$), but the contributions to $\Delta S = 0$ and $\Delta S = -1$, $B^-$ decay branching ratios can be as large as $-7.5 \times 10^{-4}$ and $2 \times 10^{-3}$, respectively. These contributions may play an important role in rare charmless $B$ decays.
Studies of B-physics greatly enrich our understanding of the interactions involving heavy quarks. In the heavy quark limit, the light quarks inside the B mesons are treated as spectators which do not affect the decay rates [1]. If the heavy quark is very heavy compared to the QCD scale $\Lambda_{QCD}$, this approximation is a good one because the effect from the light quark is suppressed by two powers in heavy quark mass compared with that of the three body decays of $b$ quark. However, in reality the $b$ quark is not infinitively heavy, the suppression factor proportional to $\Lambda_{QCD}^2/m_b^2$ may be overcomed by the enhancement factor of $16\pi^2$ in phase space because the spectator effects induced decays are two body decays [2]. Therefore spectators may affect in some way the branching ratios, especially in rare $B$ decays. We will refer the effects due to the light spectator quark inside the $B$ meson as non-spectator effects.

It has been shown that the dominant non-spectator effects at tree level can play an important role in the missing charm and the $\Lambda_b$ lifetime problems [2,3]. The non-spectator effects also have important implications for exclusive decays [4] where the corresponding effects are usually called the annihilation effects. These effects are usually assumed to be small and are neglected. It has been shown that if the annihilation contributions to $B^- \to \bar{K}^0\pi^-$ are really small, it will be possible to determine one of the fundamental parameter $\gamma$ in the unitarity triangle by measuring several $B$ decay modes [3]. It is however very difficult to calculate the annihilation contributions for exclusive decays. Without a reliable calculation, we have to find some ways to experimentally test if the annihilation contributions are small [4]. On the other hand the analogous contribution, the non-spectator contribution, in inclusive B decays may be easier to study. From this study one may also obtain some useful information about annihilation contributions for exclusive decays. In this paper we will carry out a calculation for the non-spectator contributions to the inclusive charmless $B$ meson decays in the Standard Model.

In the Standard Model the quark level effective Hamiltonian responsible for charmless $B$ decays are given by [1]
\[
H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} [V_{ub}V_{cj}^* (c_1 O_1(q) + c_2 O_2(q)) - V_{tb}V_{cq}^* \sum_{i=3-6} c_i O_i(q)] ,
\]

(1)

where

\[
O_1(q) = \bar{u} \gamma_\mu L u \bar{q} \gamma^\mu L b, \quad O_2(q) = \bar{q} \gamma_\mu L u \bar{u} \gamma^\mu L b,
\]

\[
O_{3,5}(q) = \bar{q} \gamma_\mu L b \bar{q}' \gamma^\mu L(R) q', \quad O_{4,6}(q) = \bar{q}_\alpha \gamma_\mu L b \bar{q}'_\beta \gamma^\mu L(R) q'_\alpha ,
\]

(2)

where \(L(R) = (1 \mp \gamma_5)/2\), \(q'\) is summed over \(u, d, s\), and \(q\) can be \(d\) or \(s\) depending on whether the processes are \(\Delta S = 0\) or \(\Delta S = -1\). In the above we have neglected electroweak penguin contributions. In our later discussions we will use the Wilson coefficients evaluated in Ref. [7].

There are several quark level processes correspond to non-spectator contributions. They are shown in Figs. 1 and 2. Figs. 1 and 2 are induced by tree and penguin operators, respectively. We will refer the contributions from Figs. 1a, 1b, 2a, and 2b as Usual Non-spectator (UN) contributions, while refer those from Figs. 1c, 2c and 2d, which are due to Pauli interferences, as Pauli Interference (PI) contributions. The PI contributions reduce the branching ratios. Using the optical theorem, the inclusive decay width of \(B\) can be written as the forward matrix element of the imaginary part of the transition operator \(T\),

\[
\Gamma(B) = \frac{1}{m_B} \text{Im} \langle B|T|B \rangle = \frac{1}{2m_B} \langle B|\tilde{T}|B \rangle ,
\]

(3)

where \(T\) is given by

\[
T = i \int d^4x T\{H_{\text{eff}}(x), H_{\text{eff}}(0)\} .
\]

(4)

Evaluating diagrams in Figs. 1 and 2 and neglecting terms proportional to light quark masses, we obtain

\[
\tilde{\Gamma}^q(1a) = -\frac{2 G_F^2 |V_{ub}V_{cj}^*|^2 m_b^2}{3 \pi} \left[ (N(c_1 + c_2)^2 (O_{V-A}^u - O_{V-A}^s) + 2c_1^2 (T_{V-A}^u - T_{S-P}^u) \right] ,
\]

\[
\tilde{\Gamma}(1b) = -\frac{2 G_F^2 |V_{ub}V_{ud}^*|^2 m_b^2}{3 \pi} \left[ (N(c_1 + c_2)^2 (O_{V-A}^d - O_{V-A}^s) + 2c_2^2 (T_{V-A}^d - T_{S-P}^d) \right] ,
\]

\[
\tilde{\Gamma}^q(1c) = 2 \frac{G_F^2 |V_{ub}V_{cj}^*|^2 m_b^2}{\pi} \left[ (2c_1 c_2 + 1/N(c_1^2 + c_2^2))^2 O_{V-A}^u + 2(c_1^2 + c_2^2) T_{V-A}^u \right] ,
\]

3
\[ \tilde{\Gamma}(2a) = -\frac{2}{3} G_F^2 |V_{ub} V_{td}^*|^2 m_b^2 \frac{3}{\pi} [N((c_4 + \frac{c_1}{N})^2 + (c_5 + \frac{c_6}{N})^2)(O_{V-A}^d - O_{S-P}^d) + 2(c_2^2 + c_0^2)(T_{V-P}^d - T_{S-P}^d)], \]

\[ \tilde{\Gamma}(2b) = -\frac{2}{3} G_F^2 |V_{ub} V_{eq}^*|^2 m_b^2 \frac{3}{\pi} [N((c_3 + c_4)^2(O_{V-A}^u - O_{S-P}^u) + 2c_3^2(T_{V-P}^u - T_{S-P}^u) - 6N(c_5 + c_6)^2 \tilde{O}_S^u - 12c_5 \tilde{T}_S^u], \]

\[ \tilde{\Gamma}(2c) = \frac{2}{3} G_F^2 |V_{ub} V_{eq}^*|^2 m_b^2 \frac{3}{\pi} [(2c_3 c_4 + \frac{1}{N}(c_5^2 + c_6^2))O_{V-A}^u + 2(c_5^2 + c_6^2)T_{V-A}^u - (2c_5 c_6 + \frac{1}{N}(c_5^2 + c_6^2)) \frac{2}{3} \tilde{O}_{S-P}^u - \frac{1}{6}(\tilde{O}_{V-A}^u) - 2(c_5^2 + c_6^2) \frac{2}{3} \tilde{T}_{S-P}^u - \frac{1}{6}(\tilde{T}_{V-A}^u)], \]

\[ \tilde{\Gamma}(2d) = \frac{2}{3} G_F^2 |V_{ub} V_{eq}^*|^2 m_b^2 \frac{3}{\pi} [(2c_3 c_4 + \frac{1}{N}(c_5^2 + c_6^2))O_{V-A}^d + 2(c_5^2 + c_6^2)T_{V-A}^d - (2c_5 c_6 + \frac{1}{N}(c_5^2 + c_6^2)) \frac{2}{3} \tilde{O}_{S-P}^d - \frac{1}{6}(\tilde{O}_{V-A}^d) - 2(c_5^2 + c_6^2) \frac{2}{3} \tilde{T}_{S-P}^d - \frac{1}{6}(\tilde{T}_{V-A}^d)]. \] (5)

\[ O_{V-A}^u = \bar{b}\gamma_\mu Lq\bar{q}\gamma^\mu Lb, \quad O_{S-P}^u = \bar{b}Lq\bar{q}Rb, \]

\[ T_{V-A}^u = \bar{b}\gamma_\mu LT^a q\bar{q}\gamma^\mu LT^a b, \quad T_{S-P}^u = \bar{b}LT^a q\bar{q}RT^a b, \]

\[ \tilde{O}_{V-A}^u = \bar{b}\gamma_\mu Rq\bar{q}\gamma^\mu Rb, \quad \tilde{O}_{S-P}^u = \bar{R}q\bar{q}Lb, \]

\[ \tilde{T}_{V-A}^u = \bar{b}\gamma_\mu RT^a q\bar{q}\gamma^\mu RT^a b, \quad \tilde{T}_{S-P}^u = \bar{b}RT^a q\bar{q}LT^a b. \] (6)

From the above we can obtain the non-spectator contributions to $B^-$ and $B^0$ decays using eq. (3). For $\Delta S = 0$ decays, we have

\[ \Gamma(B^- \to X) = \Gamma_0 |V_{ub} V_{ud}^*|^2 [N((c_1 \frac{c_2}{N})^2 + 2c_2^2(\varepsilon_2 - \varepsilon_1)) + 3((2c_1 c_2 + \frac{1}{N}(c_1^2 + c_2^2))B_2 + 2(c_1^2 + c_2^2)\varepsilon_1)] + \Gamma_0 |V_{ub} V_{ud}^*|^2 [N((c_1 \frac{c_2}{N})^2 + 2c_2^2(\varepsilon_2 - \varepsilon_1)) + 6N(c_5^2 + c_6^2)B_2 + 12c_5 c_6(\varepsilon_2)]
\]

\[ + 3((2c_3 c_4 + \frac{1}{N}(c_3^2 + c_4^2))B_1 + 2(c_3^2 + c_4^2)\varepsilon_1] - (2c_5 c_6 + \frac{1}{N}(c_5^2 + c_6^2)) \frac{2}{3} \tilde{B}_2 - \frac{1}{6}(\tilde{B}_1) - 2(c_5^2 + c_6^2) \frac{2}{3} \tilde{E}_2 - \frac{1}{6}(\tilde{E}_1)], \]

\[ \Gamma(B^0 \to X) = \Gamma_0 |V_{ub} V_{ud}^*|^2 [N(c_1 \frac{c_2}{N})^2 + 2c_2^2(\varepsilon_2 - \varepsilon_1)] + 3\Gamma_0 |V_{ub} V_{ud}^*|^2 [N((c_1 \frac{c_2}{N})^2 + 2c_2^2(\varepsilon_2 - \varepsilon_1)) + 2(c_1^2 + c_2^2)\varepsilon_1] + 2(c_4^2 + c_6^2)(\varepsilon_2 - \varepsilon_1)] \]
\begin{align*}
&+ 3[(2c_3c_4 + \frac{1}{N}(c_3^2 + c_4^2))B_1 + 2(c_3^2 + c_4^2)\varepsilon_1 \\
&- (2c_5c_6 + \frac{1}{N}(c_5^2 + c_6^2))(\frac{2}{3}\tilde{B}_2 - \frac{1}{6}\tilde{B}_1) - 2(c_5^2 + c_6^2)(\frac{2}{3}\tilde{\varepsilon}_2 - \frac{1}{6}\tilde{\varepsilon}_1)] \tag{7}
\end{align*}

And for $\Delta S = -1$ decays, we have

\begin{align*}
\Gamma(B^+ \to X_s) &= \Gamma_0|V_{ub}V_{us}^*|^2\{(N(\frac{c_1}{N} + c_2)^2(B_2 - B_1) + 2c_2^2(\varepsilon_2 - \varepsilon_1)) \\
&+ 3[(2c_1c_2 + \frac{1}{N}(c_1^2 + c_2^2))B_1 + 2(c_1^2 + c_2^2)\varepsilon_1]\}
&+ \Gamma_0|V_{ub}V_{ts}^*|^2\{(N(\frac{c_3}{N} + c_4)^2(B_2 - B_1) + 2c_4^2(\varepsilon_2 - \varepsilon_1) \\
&+ 6N(\frac{c_3}{N} + c_4)^2\tilde{B}_2 + 12c_4^2\tilde{\varepsilon}_2) \\
&+ 3[(2c_3c_4 + \frac{1}{N}(c_3^2 + c_4^2))B_1 + 2(c_3^2 + c_4^2)\varepsilon_1 \\
&- (2c_5c_6 + \frac{1}{N}(c_5^2 + c_6^2))(\frac{2}{3}\tilde{B}_2 - \frac{1}{6}\tilde{B}_1) - 2(c_5^2 + c_6^2)(\frac{2}{3}\tilde{\varepsilon}_2 - \frac{1}{6}\tilde{\varepsilon}_1)]\}, \\
\Gamma(\bar{B}^0 \to X_s) &= 3\Gamma_0|V_{ub}V_{us}^*|^2[(2c_3c_4 + \frac{1}{N}(c_3^2 + c_4^2))B_1 + 2(c_3^2 + c_4^2)\varepsilon_1 \\
&- (2c_5c_6 + \frac{1}{N}(c_5^2 + c_6^2))(\frac{2}{3}\tilde{B}_2 - \frac{1}{6}\tilde{B}_1) - 2(c_5^2 + c_6^2)(\frac{2}{3}\tilde{\varepsilon}_2 - \frac{1}{6}\tilde{\varepsilon}_1)] \tag{8}
\end{align*}

where $\Gamma_0 = G_F^2 m_0^2 m_B f_B^2 / 12\pi$, and the parameters $B_i(\tilde{B}_i)$ and $\varepsilon_i(\tilde{\varepsilon}_i)$ are defined as follows,

\begin{align*}
< B|\bar{b}\gamma_{\mu}Lq\bar{q}\gamma_{\mu}Lb|B> &= \frac{f_B^2 m_B^2}{4} B_1, \\
< B|\bar{b}Lq\bar{q}Rb|B> &= \frac{f_B^2 m_B^2}{4} B_2,
\end{align*}

\begin{align*}
< B|\bar{b}\gamma_{\mu}LT^a q\bar{q}\gamma_{\mu}LT^a b|B> &= \frac{f_B^2 m_B^2}{4} \varepsilon_1, \\
< B|\bar{b}LT^a q\bar{q} RT^a b|B> &= \frac{f_B^2 m_B^2}{4} \varepsilon_2,
\end{align*}

\begin{align*}
< B|\bar{b}\gamma_{\mu}Rq\bar{q}\gamma_{\mu}Rb|B> &= \frac{f_B^2 m_B^2}{4} \tilde{B}_1, \\
< B|\bar{b}Rq\bar{q}Lb|B> &= \frac{f_B^2 m_B^2}{4} \tilde{\varepsilon}_1, \\
< B|\bar{b}RT^a q\bar{q}LT^a b|B> &= \frac{f_B^2 m_B^2}{4} \tilde{\varepsilon}_2. 
\end{align*}

The above definitions are inspired by the factorization approximation calculation. In this approximation, $B_i = \tilde{B}_i = 1$ and $\varepsilon_i = \tilde{\varepsilon}_i = 0$. Conservation of strong interaction implies $B_i = \tilde{B}_i$ and $\varepsilon_i = \tilde{\varepsilon}_i$. There have been some attempts to calculate $\varepsilon_i$ using the QCD sum rules. The numbers obtained are $\varepsilon_1 \approx -0.15$ and $\varepsilon_2 \approx 0$. To see how the results change with hadronic parameters, we will take two sets of representative values in our latter analyses: a) $B_i(\tilde{B}_i) = 1$, $\varepsilon_i(\tilde{\varepsilon}_i) = 0$, and b) $B_i(\tilde{B}_i) = 1$, $\varepsilon_1(\tilde{\varepsilon}_1) = -0.15$, $\varepsilon_2(\tilde{\varepsilon}_2) = 0$. The numerical values also depend on the values of several KM matrix elements and the B decay.
constant $f_B$. We will use the values for these parameters given in the table caption for illustration. One can easily find out the changes using eq. (7) and (8) for other values of the parameters involved. Our numerical results for the branching ratios are given in Table 1.

In the factorization approximation, $\bar{B}^0$ decays do not receive tree non-spectator contributions and $B^-$ decays only receive PI contributions. Note also that even non-factorizable contributions are included, the tree PI terms do not contribute to $\bar{B}^0$ decays.

For $\Delta S = 0$ decays, the non-spectator contributions are dominated by the PI contribution at tree level which reduces the total branching ratio by $-2.8 \times 10^{-4}$ in the factorization approximation. Non-factorizable effects can change the situation significantly. Using $\varepsilon_1 = -0.15$ and keeping the other parameters unchanged, the total branching ratio can be reduced by $-7.6 \times 10^{-4}$ for $B^-$ decays, and the branching ratio for $\bar{B}^0$ decay can be increased by $1.4 \times 10^{-4}$ from UN contributions. These effects although small for total branching ratios, but when study rare charmless decays, it may play an important role. For example for even just a few percent of the non-spectator contributions find their way to $B^- \to \pi^-\pi^0$, the branching ratio for this exclusive decay can change more than 10%. The penguin non-spectator contributions are much smaller ($< 2 \times 10^{-5}$) and do not play an important role.

The branching ratios for charmless and $\Delta S = 0$, $B^-$ and $\bar{B}^0$ decays are of order $5 \times 10^{-3}$ from the three body $b$ quark decays \[.\] The non-spectator contributions can reach 6$\% \sim 12\%$ of the main contributions. Also the non-spectator contributions decrease the branching ratio for $B^-$ and increase the branching ratio for $\bar{B}^0$. Experiments in the future may be able to observe these effects.

For $\Delta S = -1$ $B$ meson decays, the roles played by tree and penguin non-spectator contributions are reversed. The non-spectator contributions can increase the branching ratio for $B^-$ decays by as much as $1.9 \times 10^{-3}$. $\bar{B}^0$ decays only receive PI contributions and the branching ratio can be reduced at a few times of $10^{-4}$ level. The tree non-spectator contributions to $B^-$ can reduce the total branching ratio by a few times $10^{-5}$. This is small, but may still play an important role in the study of rare $B^- \to \bar{K}^0\pi^-$ decay. Usually the tree amplitude for this decay is assumed to be extremely small. If this is true this decay
mode can be used in combination with several other decays, for example, $B^- \rightarrow K^-\pi^0$ and $B^- \rightarrow \pi^-\pi^0$ decays, to determine the parameter $\gamma$ in the KM unitarity triangle \cite{5}. If annihilation contribution to the branching ratio of $B^- \rightarrow \bar{K}^0\pi^-$ decay is large $O(10^{-6})$ (10% of the inclusive non-spectator contributions), it will cause large uncertainty in the determination of the angle $\gamma$. However at present we do have reliable ways to make a vigorous calculation. More detailed study is required.

The non-spectator contributions to the total branching ratios for $\Delta S = -1$ $B$ mesons are small, but can be 20% of the three body b quark decay contribution (1%) \cite{3} to charmless $B$ meson decays. This contribution can not be neglected. Also the non-spectator contributions affect $B^-$ and $\bar{B}^0$ differently. Experiments in the future may observed such effects. Another important feature of the non-spectator contributions is that the decay modes induced by non-spectator effects are two body type. Their effect may be more eminent if kinematic cut requiring the decays to be two hard jets with small invariant masses is applied.

We would like to comment on the penguin non-spectator effects on the missing charm and the $\Lambda_b$ lifetime problems before conclude the paper. For this discussion, we will also need to consider final states with charm quarks because this is the main non-spectator contribution. It has been shown that the tree non-spectator contributions can be important \cite{2}. From factorization calculation without the PI contributions, one might think that the penguin contributions to be important. In this case, the dominant tree non-spectator contribution is from $bd \rightarrow cu$ which is proportional to $(c_1 + c_2/N)^2$, whereas the penguin non-spectator contribution is dominated by $bd \rightarrow sd$ as can be seen from our previous discussions. Because the accidental cancellation between $c_1$ and $c_2/N$ for $N = 3$, the penguin contribution is about 20 times of the tree contribution in the factorization approximation. However, this result is very sensitive to the values for $\varepsilon_i$. With $\varepsilon_1 = -0.15$ for example, the tree annihilation is 10 times larger than penguin contributions. Also, when PI contributions are included, the main tree contribution is proportional to $c_1c_2$ which is not small. The tree non-spectator contributions turn out to be 15 to 30 times larger than the penguin non-spectator contributions.
We also carried out a detailed calculation for the penguin non-spectator contributions to the $\Lambda_b$ lifetime. We again find that the penguin non-spectator contributions are only a few percent of the tree non-spectator contributions. We conclude that the penguin non-spectator contributions do not play an important role in solving the missing charm and $\Lambda_b$ lifetime problems.

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TABLE I. The annihilation contributions to the branching ratios of $B$ mesons for a) $B_1 = B_2 = 1$, $\varepsilon_1 = \varepsilon_2 = 0$, and b) $B_1 = B_2 = 1$, $\varepsilon_1 = -0.15$, $\varepsilon_2 = 0$, with $m_b = 4.8$ GeV, $f_B = 0.2$ GeV, $|V_{ub}|/|V_{cb}| = 0.08$, $|V_{cb}| = |V_{ts}| = 0.038$, and $|V_{td}| = |V_{ub}|$.

| $\Delta S = 0$ | $B^-$ | a | b | $\bar{B}^0$ | a | b |
|----------------|-------|---|---|------------|---|---|
| Tree           | UN    | 0 | $1.1 \times 10^{-5}$ | 0 | $1.4 \times 10^{-4}$ |
|                | PI    | $-2.8 \times 10^{-4}$ | $-7.6 \times 10^{-4}$ | 0 | 0 |
| Penguin        | UN    | $1.2 \times 10^{-5}$ | $1.2 \times 10^{-5}$ | 0 | $1.14 \times 10^{-6}$ |
|                | PI    | $-0.7 \times 10^{-6}$ | $-1.4 \times 10^{-6}$ | $-0.68 \times 10^{-6}$ | $-1.36 \times 10^{-6}$ |
| $\Delta S = -1$ | $B^-$ | a | b | $\bar{B}^0$ | a | b |
| Tree           | UN    | 0 | $5.7 \times 10^{-7}$ | 0 | 0 |
|                | PI    | $-1.4 \times 10^{-5}$ | $-3.9 \times 10^{-5}$ | 0 | 0 |
| Penguin        | UN    | $1.9 \times 10^{-3}$ | $1.9 \times 10^{-3}$ | 0 | 0 |
|                | PI    | $-1.1 \times 10^{-4}$ | $-2.2 \times 10^{-4}$ | $-1.1 \times 10^{-4}$ | $-2.1 \times 10^{-4}$ |
FIG. 1. Diagrams for tree non-spectator contributions to charmless $B$ meson decays.

FIG. 2. Diagrams for penguin non-spectator contributions to charmless $B$ meson decays.