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Space-like Penguin effects in B_c decays*

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Abstract. The space-like penguin contributions to branching ratios and CP asymmetries in charmless decays of B_c to two pseudoscalar mesons are studied using the next-to-leading order low energy effective Hamiltonian and factorization approximation. Both the gluonic penguin and the electroweak penguin diagrams are considered. In addition the annihilation diagram contributions are also taken in account. We find that the space-like penguin effects are significant.

1 Introduction

The weak decays of B mesons offer a direct way to determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and to explore the origin of CP violation. Penguin diagrams can play an important role in charmless B decays. In most cases, attentions were paid to time-like penguin diagram in the literature, and the space-like penguin diagram is considered negligible because of the form factor suppression. In [1], space-like penguin diagram contribution to the branching ratios and CP violating asymmetries in B_u^-, B^0, B_s^0 decays are considered. The result shows that the space-like penguin amplitude can be enhanced by the hadronic matrix element involving (V-A) (V+A) or (S-P) (S+P) currents, and the space-like penguin effects are large in most charmless B decays.

B_c meson is considered as the next and the last member of B mesons. Its physics has got intensive attention recently [2, 3]. B_c decay has its own characteristics. The obvious one is that B_c carries c and b quarks, which are both heavy. So, B_c decays can be interesting candidates for testing the spectator ansatz. We assume that spectator approximation can be applied in B_c decays. In our paper, we will consider only b quark decays and take c quark as a spectator. From [3], the future accelerator, Large Hardron Collider (LHC), will produce $2.1 \times 10^8 B_c$ per year, and can be a good place to study B_c decays.

In this paper, we study space-like penguin diagram effects in B_c decays to two pseudoscalars, and we concentrate on the charmless B_c decays, because penguin diagram plays an important role in these decays. We use the next-to-leading order low energy effective Hamiltonian and factorization approximation to calculate the branching ratios and CP violating asymmetries. In B_c charmless decays, the annihilation diagram has the same order amplitude as the tree diagram. So the annihilation diagrams should be also taken into account. The result shows that the space-like penguin diagram contributions in B_c charmless decays are large and cannot be neglected.

2 Effective Hamiltonian and factorization approximation

We assume spectator approximation in B_c decays: the c quark is a spectator and the b quark decays to other light quarks. According to [4], the next-to-leading order low energy effective Hamiltonian describing $|\Delta B| = 1$ transitions is given at the renormalization scale $\mu = O(m_b)$ as

$$\mathcal{H}_{eff}(|\Delta B| = 1) = \frac{G_F}{\sqrt{2}} \left[\sum_{q=u,c} v_q \left\{ Q_1^q C_1(\mu) + Q_2^q C_2(\mu) + \sum_{k=3}^{10} Q_k C_k(\mu) \right\} \right] + H.C. \qquad (1)$$

The CKM factors v_q are defined as

$$v_q = \begin{cases} V_{qd}^* V_{qb} & \text{for } b \to d \text{ transitions} \\ V_{qs}^* V_{qb} & \text{for } b \to s \text{ transitions.} \end{cases} \qquad (2)$$

The ten operators Q_1^u, Q_2^u, Q_3, $\cdots$, Q_{10} are given as the following forms:

$$Q_1^u = (\bar{q}_\alpha u_\beta)_{V-A} (\bar{u}_\beta b_\alpha)_{V-A}$$
$$Q_2^u = (\bar{q} u)_{V-A} (\bar{u} b)_{V-A}$$
$$Q_{3(5)} = (\bar{q} b)_{V-A} \sum_{q'} (\bar{q}' q')_{V-A(V+A)}$$

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$$Q_{4(6)} = (\bar{q}_\alpha b_\beta)_{V-A} \sum_{q'} \left(\bar{q}'_\beta q'_\alpha\right)_{V-A(V+A)}$$

$$Q_{7(9)} = \frac{3}{2}(\bar{q}b)_{V-A} \sum_{q'} e_{q'} \left(q' q'\right)_{V+A(V-A)}$$

$$Q_{8(10)} = \frac{3}{2}\left(\bar{q}_\alpha b_\beta\right)_{V-A} \sum_{q'} e_{q'} \left(\bar{q}'_\beta q'_\alpha\right)_{V+A(V-A)} \qquad (3)$$

where Q_1^u and Q_2^u are the current-current operators, and the current-current operators Q_1^c and Q_2^c can be obtained from Q_1^u and Q_2^u through the substitution of $u \to c$. Q_3, $\cdots$, Q_6 are the QCD penguin operators, whereas Q_7, $\cdots$, Q_{10} are the electroweak penguin operators. The quark $q = d$ or s for $b \to d$ or s transitions, respectively; the indices α, β are $SU(3)_c$ color indices; $(V \pm A)$ refer to $\gamma_\mu (1 \pm \gamma_5)$.

It is useful to use the renormalization scheme independent Wilson coefficient functions [5]:

$$\bar{\mathbf{C}}(\mu) = \left[\hat{1} + \frac{\alpha_s(\mu)}{4\pi}\hat{r}_s^T + \frac{\alpha(\mu)}{4\pi}\hat{r}_e^T\right] \cdot \mathbf{C}(\mu) \,, \qquad (4)$$

where $\mathbf{C}(\mu)$, $\bar{\mathbf{C}}(\mu)$ are all column vectors. The matrix elements are:

$$< \mathbf{Q}^T(\mu) \cdot \mathbf{C}(\mu) > \equiv < \mathbf{Q}^T >_0 \cdot \mathbf{C}'(\mu) \qquad (5)$$

where $< \mathbf{Q} >_0$ denote the tree level matrix elements of these operators, and $\mathbf{C}'(\mu)$ are defined as

$$\begin{aligned}
&C_1' = \bar{C}_1 \,, \quad C_2' = \bar{C}_2 \,, \quad C_3' = \bar{C}_3 - P_s/3 \,, \\
&C_4' = \bar{C}_4 + P_s \,, \quad C_5' = \bar{C}_5 - P_s/3 \,, \quad C_6' = \bar{C}_6 + P_s \,, \\
&C_7' = \bar{C}_7 + P_e \,, \quad C_8' = \bar{C}_8 \,, \\
&C_9' = \bar{C}_9 + P_e \,, \quad C_{10}' = \bar{C}_{10} \,, \qquad (6)
\end{aligned}$$

where $P_{s,e}$ are given by

$$\begin{aligned}
P_s &= \frac{\alpha_s}{8\pi}\bar{C}_2(\mu)\left[\frac{10}{9} - G(m_q, q, \mu)\right] \,, \\
P_e &= \frac{\alpha_{em}}{9\pi}\left(3\bar{C}_1 + \bar{C}_2(\mu)\right)\left[\frac{10}{9} - G(m_q, q, \mu)\right] \,, \\
G(m, q, \mu) &= -4\int_0^1 dx\, x(1-x)\ln\left[\frac{m^2 - x(1-x)q^2}{\mu^2}\right] \,, (7)
\end{aligned}$$

here $q = u, c$. The numerical values of the renormalization scheme independent Wilson Coefficients $\bar{C}_i(\mu)$ at $\mu = O(m_b)$ are [6]

$$\begin{aligned}
&\bar{c}_1 = -0.313 \,, \quad \bar{c}_2 = 1.150 \,, \quad \bar{c}_3 = 0.017 \,, \\
&\bar{c}_4 = -0.037 \,, \quad \bar{c}_5 = 0.010 \,, \quad \bar{c}_6 = -0.046 \,, \\
&\bar{c}_7 = -0.001 \cdot \alpha_{em} \,, \quad \bar{c}_8 = 0.049 \cdot \alpha_{em} \,, \\
&\bar{c}_9 = -1.321 \cdot \alpha_{em} \,, \quad \bar{c}_{10} = 0.267 \cdot \alpha_{em} \,. \qquad (8)
\end{aligned}$$

In (7), q^2 denotes the momentum transfer squared of the virtual gluons, photons, and Z^0 appearing in the QCD and electroweak penguin diagrams respectively. So, the Wilson coefficients C_1' depend on q^2. We adopt a simple kinematic picture [1] for two body decays $B \to PP'$ as illustrated in Fig. 1.

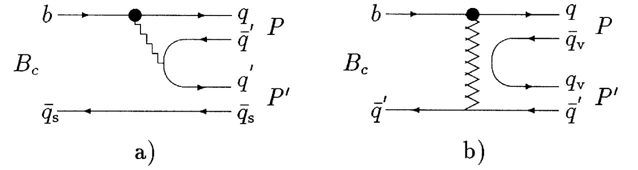

Fig. 1. Penguin diagrams for a B_c meson decaying into two light pseudoscalar mesons P and P' **a** the time-like penguin diagram; **b** the space-like penguin diagram. The subscripts "v" denote "vacuum". The *dark dot* stands for the contraction of the W-loop

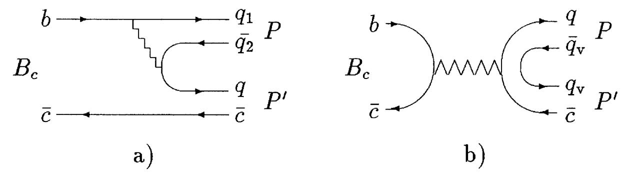

Fig. 2. The Tree diagram and the Annihilation diagram in B_c decays. **a** the Tree diagram. **b** the Annihilation diagram

The average value of q^2 can be given by

$$< q^2 >= m_b^2 + m_q^2 - 2m_b E_q \qquad (9)$$

where E_q is determined from

$$E_q + \sqrt{E_q^2 - m_q^2 + m_{q'}^2} + \sqrt{4\left(E_q^2 - m_q^2\right) + m_{q'}^2} = m_b \quad (10)$$

for the time-like penguin diagram; and

$$E_q + \sqrt{E_q^2 - m_q^2 + m_{q'}^2} + = m_b + m_{q'} \qquad (11)$$

for the space-like penguin diagram.

In exclusive nonleptonic decays, the current-current operator matrix element can be calculated by factorization approximation and BSW method [7].

For the tree diagram of Fig 2a which correponds to $b \to q_1\bar{q}_2 q$, the matrix element for four-quark operator is defined as:

$$\begin{aligned}
M_{q_1 q_2 q}^{PP'} &\equiv < PP'|\left(\bar{q}_1 q_2\right)_{V-A}(\bar{q}b)_{V-A}|B_c^- > \\
&= < P|\left(\bar{q}_1 q_2\right)_{V-A}|0 >< P'|(\bar{q}b)_{V-A}|B_c^- > \\
&= -i f_P^{\bar{q}_1 q_2} f_+^{B_c P'}\left(M_P^2\right) \\
&\quad \left(M_{B_c}^2 - M_{P'}^2 - \frac{M_{B_c} - M_{P'}}{M_{B_c} + M_{P'}} M_P^2\right) \qquad (12)
\end{aligned}$$

where $f_+^{B_c P'}\left(m_P^2\right) = \frac{f_+^{B_c P'}(0)}{1 - M_P^2/\left(M_{B_c}^{pole}\right)^2} \cdot f_+^{B_c P'}(0)$ can be calculated in BSW model, and $M_{B_c}^{pole} = 6.30\,\mathrm{GeV}$. For the time-like penguin diagram, this factorization method is applied to calculate the time-like penguin operator matrix element.

For the annihilation diagram of Fig. 2b corresponds to $b\bar{c} \to q\bar{c}$, the matrix element is [8]:

$$S_{qcc}^{PP'} \equiv < PP'|(\bar{q}c)_{V-A}(\bar{c}b)_{V-A}|B_c^- >$$

Table 1. The Branching Ratios of B_c decaying to two pseudoscalar

Decay Mode	Br					
	Only Tree	Tree+Anni	Tree+Anni+T-like		Tree+Anni+T-like+S-like	
			QCD	QCD+EW	QCD	QCD+EW
$B_c^- \to \pi^- \bar{D}^0$	1.12×10^{-5}	9.60×10^{-6}	8.31×10^{-6}	8.29×10^{-6}	2.27×10^{-6}	2.32×10^{-6}
$B_c^- \to K^- \bar{D}^0$	8.63×10^{-7}	2.81×10^{-6}	1.94×10^{-5}	1.99×10^{-5}	4.82×10^{-5}	4.76×10^{-5}
$B_c^- \to \pi^0 D^-$	2.54×10^{-8}	1.20×10^{-7}	5.21×10^{-7}	3.73×10^{-7}	2.01×10^{-5}	1.91×10^{-5}
$B_c^- \to \eta D^-$	1.77×10^{-8}	3.00×10^{-9}	8.05×10^{-6}	7.73×10^{-6}	7.09×10^{-6}	7.10×10^{-6}
$B_c^- \to \eta' D^-$	1.76×10^{-8}	9.88×10^{-9}	6.45×10^{-5}	6.43×10^{-5}	6.34×10^{-5}	6.34×10^{-5}
$B_c^- \to \eta D_s^-$	9.03×10^{-10}	1.53×10^{-7}	8.62×10^{-6}	2.71×10^{-6}	9.02×10^{-6}	8.87×10^{-6}
$B_c^- \to \eta' D_s^-$	4.40×10^{-10}	1.26×10^{-7}	6.09×10^{-6}	9.18×10^{-6}	1.18×10^{-5}	1.17×10^{-5}
$B_c^- \to K^0 D_s^-$	0	3.41×10^{-8}	1.29×10^{-6}	1.27×10^{-6}	1.99×10^{-6}	1.96×10^{-5}
$B_c^- \to \bar{K}^0 D^-$	0	5.87×10^{-7}	1.60×10^{-5}	1.58×10^{-5}	3.60×10^{-5}	3.55×10^{-5}

$$
\begin{aligned}
&= < PP'|(\bar{q}c)_{V-A}|0 >< 0|(\bar{c}'b)_{V-A}|B_c^- > \\
&= i f_{B_c} f_+^a \left(M_{B_c}^2\right) \\
&\quad \left(M_P^2 - M_{P'}^2 - \frac{M_P - M_{P'}}{M_P + M_{P'}} M_{B_c}^2\right) \qquad (13)
\end{aligned}
$$

The matrix elements are computed at momentum transfer $q^2 = M_{B_c}^2$. We take the asymptotic form factor $f_+^a\left(M_{B_c}^2\right) = i16\pi\alpha_s f_{B_c}^2/M_{B_c}^2$ [9]. One point should be noted: for the annihilation diagram, $C_1' = \bar{C}_2, C_2' = \bar{C}_1$.

In B_c decays, the annihilation diagram is enhanced by the CKM factor v_c. For the $b \to d$ process, $|\frac{v_c}{v_u}| \approx 3$; for $b \to s$ process, $|\frac{v_c}{v_u}| \approx 57$. So, the annihilation diagram should be taken into account in B_c decays.

For the space-like penguin diagram, just like the annihilation diagram, its factorization method is the same as that of the annihilation diagram.

3 Numerical calculation

The decay width for a B_c meson at rest decaying into two pseudoscalars is

$$
\Gamma\left(B_c \to PP'\right) = \frac{1}{8\pi} | < PP'|H_{eff}|B_c > |^2 \frac{|\mathbf{p}|}{M_{B_c}^2} \qquad (14)
$$

where

$$
|\mathbf{p}| = \frac{\left[\left(M_{B_c}^2 - (M_P + M_{P'})^2\right)\left(M_{B_c}^2 - (M_P - M_{P'})^2\right)\right]^{\frac{1}{2}}}{2M_{B_c}} \qquad (15)
$$

is the momentum of the pseudoscalar meson P or P'. The corresponding branching ratios are given by

$$
Br\left(B_c \to PP'\right) = \frac{\Gamma\left(B_c \to PP'\right)}{\Gamma_{tot}^{B_c}} . \qquad (16)
$$

In our numerical calculation, we take [10] $\Gamma_{tot}^{B_c} = 1.32 \times 10^{-12}$ GeV.

The B_c meson decay amplitude can be generally expressed as

$$
\left\langle PP' \left| H_{eff} \right| B_c^- \right\rangle = \frac{G_F}{\sqrt{2}} \sum_{q=u,c} v_q F_q . \qquad (17)
$$

where $q = u, c$, and F_q including the tree and and annihilation and penguin amplitude. The CP-violating asymmetry can be given by

$$
\begin{aligned}
\mathcal{A}_{cp} &\equiv \frac{\Gamma\left(B_c^- \to PP'\right) - \Gamma\left(B_c^+ \to \bar{P}\bar{P}'\right)}{\Gamma\left(B_c^- \to PP'\right) + \Gamma\left(B_c^+ \to \bar{P}\bar{P}'\right)} \\
&= \frac{2Im\left(v_u v_c^*\right) Im\left(F_c/F_u\right)}{|v_u|^2 + |v_c|^2 |F_c/F_u|^2 + 2Re\left(v_u v_c^*\right) Re\left(F_c/F_u\right)} . \qquad (18)
\end{aligned}
$$

We take the decay $B_c^- \to \eta D^-$ as an example to illustrate the calculation of branching ratio Br and CP asymmetry $\mathcal{A}_{cp}$ including space-like penguin diagram.

$$
\begin{aligned}
&\left\langle \eta D^- \left| H_{eff} \right| B_c^- \right\rangle \\
&= \frac{G_F}{\sqrt{2}} \sum_{q=u,c} v_q \Bigg[\Bigg(a_2\delta_{uq} + a_3 + a_4 - a_6 \quad + a_8 - a_9/2 \\
&\quad - a_{10} + \frac{2M_\eta^2}{(m_d + m_d)(m_b - m_d)} (a_5 - a_7/2) \Bigg) M_{ddd}^{\eta D^-} \\
&\quad + \Bigg(a_2\delta_{cq} + a_3 + \frac{2M_{B_c}^2}{(m_d - m_c)(m_b + m_c)} \\
&\quad \times (a_5 + a_7) + a_9 \Bigg) S_{dcc}^{\eta D^-} \Bigg] . \qquad (19)
\end{aligned}
$$

where a_k is defined as

$$
\begin{aligned}
a_{2i-1} &\equiv \frac{C_{2i-1}'}{3} + C_{2i}' , \\
a_{2i} &\equiv C_{2i-1}' + \frac{C_{2i}'}{3}, \ (i = 1,2,3,4,5)
\end{aligned}
$$

and

$$
M_{ddd}^{\eta D^-} = i f_\eta^{\bar{d}d} f_+^{B_c^- D^-} \left(M_\eta^2\right) \Big[\left(M_{B_c}^2 - M_{D^-}^2\right)
$$

Table 2. The CP Asymmetries of B_c decaying to two pseudoscalar. Where the "Tree" means the tree diagram contribution, "Anni" means the annihilation diagram contribution, "T-like" denotes the time-like penguin contributions, the "S-like" denotes the space-like penguin contributions, "QCD" means QCD penguin contributions, and "EW" means electro-weak penguin contributions

Decay Mode	$\mathcal{A}_{cp}$				
	Tree+Anni	Tree+Anni+T-like		Tree+Anni+T-like+S-like	
		QCD	QCD+EW	QCD	QCD+EW
$B_c^- \to \pi^- \bar{D}^0$	−15.1%	−6.8%	−6.8%	−80.6%	−80.1%
$B_c^- \to K^- \bar{D}^0$	92.6%	−0.7%	−0.7%	19.7%	19.7%
$B_c^- \to \pi^0 D^-$	92.7%	27.9%	34.1%	15.1%	15.1%
$B_c^- \to \eta D^-$	−88.6%	14.8%	15.1%	9.2%	9.3%
$B_c^- \to \eta' D^-$	−47.7%	12.1%	12.1%	11.6%	11.6%
$B_c^- \to \eta D_s^-$	−13.4%	−0.7%	−1.7%	−1.4%	−1.4%
$B_c^- \to \eta' D_s^-$	11.8%	−1.8%	−1.4%	0.3%	0.3%
$B_c^- \to K^0 D_s^-$	0	20.2%	20.4%	−0.6%	−0.6%
$B_c^- \to \bar{K}^0 D^-$	0	−1.3%	−1.3%	0.1%	0.1%

$$- \frac{M_{B_c} - M_{D^-}}{M_{B_c} + M_{D^-}} M_\eta^2 \Bigg]$$

$$S_{dcc}^{\eta D^-} = \frac{1}{\sqrt{3}} f_{B_c} f_+^a \left(M_{B_c}^2\right) \left[\left(M_\eta^2 - M_{D^-}^2\right) - \frac{M_\eta - M_{D^-}}{M_\eta + M_{D^-}} M_{B_c}^2 \right] \quad (20)$$

where $\frac{1}{\sqrt{3}}$ arises from $\eta = \frac{\bar{u}u + \bar{d}d - \bar{s}s}{\sqrt{3}}$. The $a_2 \delta_{cq}$ term in (19) is the annihilation diagram contribution.

The numerical results of the space-like penguin contributions to the branching ratios and CP-violating asymmetries are given in Table 1 and 2. We calculate the branching ratios and CP-violating asymmetries with the tree and annihilation and time-like penguin contributions for comparison. All the parameters such as meson decay constants, form factors and quark masses needed in our calculation are taken as $f_{\pi^\pm} = 0.13\,\mathrm{GeV}$, $f_K = 0.160\,\mathrm{GeV}$ [11], $f_{\pi^0}^{\bar{u}u} = -f_{\pi^0}^{\bar{d}d} = f_{\pi^\pm}/\sqrt{2}$. $f_\eta^{\bar{u}u} = f_\eta^{\bar{d}d} = -f_\eta^{\bar{s}s} = 0.077\,\mathrm{GeV}$, $f_{\eta'}^{\bar{u}u} = f_{\eta'}^{\bar{d}d} = f_{\eta'}^{\bar{s}s}/2 = 0.054\,\mathrm{GeV}$ [12], $f_{B_c} = 0.5\,\mathrm{GeV}$ [3], $f_+^{B_c^- D^-}(0) = 0.595$, $f_+^{B_c^- D_s^-}(0) = 0.605$, $m_u = 0.005\,\mathrm{GeV}$, $m_d = 0.001\,\mathrm{GeV}$, $m_s = 0.2\,\mathrm{GeV}$, $m_c = 1.5\,\mathrm{GeV}$, $m_b = 4.5\,\mathrm{GeV}$, $M_{B_c} = 6.27\,\mathrm{GeV}$ and the Wolfenstein parametrized CKM parameters are [13]: $\lambda = 0.22$, $A = 0.8$, $\eta = 0.34$, $\rho = -0.12$.

4 Conclusion and discussion

From Table 1 and 2 we can see the following features:

(i) For most of the charmless decays, space-like penguin contributions to branching ratios are large. The corrections to the branching ratio and CP violating asymmetries are more than 100%.
(ii) For space-like penguin in B_c decays, the contributions of the electro-weak penguins are negligible.
(iii) The annihilation diagram contribution can not be negligible in B_c decays.

The reason for the large space-like penguin effects can be explained as follows:

(i) When calculating the matrix elememt of $(V-A)(V+A)$ current $< PP'|(\bar{q}b)_{V-A}(\bar{c}c)_{V+A}|B_c >$, there will appear a factor $\frac{2m_{B_c}^2}{(m_q - m_c)(m_b + m_c)}$, this factor will enhance the space-like penguin effects.
(ii) The form factor $f_+^a\left(m_{B_c}^2\right)$ is not a suppression factor as usually considered. In B_c decays, $f_+^a\left(m_{B_c}^2\right) = 0.077$, so combine with $f_{B_c} = 0.5$, the annihilation or space-like penguin matrix element $S^{PP'}$ is nearly as that of the tree and time-like penguin matrix element $M^{PP'}$.
(iii) The quark mass is an important and sensitive parameter. In our calculation, we have used the current mass. The values of quark mass will have direct effect on the penguin amplitude. Other effects, such as nonfactorization effect, final state interation can provide many uncertainties.

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