The role of electroweak penguin and magnetic dipole QCD penguin on hadronic b Quark Decays

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(Received 16 March 2008, in final form 24 September 2009)

Abstract

This research, works with the effective Hamiltonian and the quark model. Using, the decay rates of matter-antimatter of b quark was investigated. We described the effective Hamiltonian theory which was applied to the calculation of current-current (2,1\(Q\)), QCD penguin (3,...,6\(Q\)), magnetic dipole (8\(Q\)) and electroweak penguin (7,...,10\(Q'\)) decay rates. The gluonic penguin structure of hadronic b decays \(kk\rightarrow ik\) was studied through the Wilson coefficients of the effective Hamiltonian. The branching ratios of the Tree-Level, effective Hamiltonian, effective Hamiltonian including electroweak penguin, effective Hamiltonian including magnetic dipole and the effective Hamiltonian including electroweak penguin and magnetic dipole b quark decays \(k\rightarrow ik\) have been calculated. It was shown that, the electroweak penguin and magnetic dipole contributions in b quark decays are small and current-current operators are dominated.

Keywords: b quark, QCD penguin, electroweak penguin, magnetic dipole

1. Introduction

Conservation of the gluonic current requires the \(kk\rightarrow k\bar{q}g\) vertex to have the structure [1,2]:

\[
\Gamma_{\mu}^{\mu}(q^2) = \left(\frac{ig_s}{4\pi^2}\right)\bar{u}_k(p_k)T^a\gamma_{\mu}(q^2)u_b(p_b),
\]

where,

\[
V_{\mu}(q^2) = (2g_{\mu\nu} - q_{\mu}q_{\nu})\gamma^\nu[F_1^{L}(q^2)P_L F_1^{R}(q^2)P_R] + i\sigma_{\mu\nu}q^{\nu}[F_2^{L}(q^2)P_L F_2^{R}(q^2)P_R].
\]

Here \(F_1\) and \(F_2\) are respectively the electric (monopole) and magnetic (dipole) form factors, \(q = q_{\bar{q}} = p_b - p_k\) is the gluon four momentum, \(P_{L,R} = (1\mp\gamma_5)/2\) are the chirality projection operators and \(T^a (a = 1,...,8)\) are the \(SU(3)_c\) generators normalized to \(Tr(T^aT^b) = 3\delta^{ab}/2\).

The \(kk\rightarrow k\bar{q}g\) vertex is

\[
\tilde{\Gamma}_\mu^{\mu}(q^2) = -\left(\frac{ig_s}{4\pi^2}\right)\bar{v}_k(p_k)T^a\tilde{\gamma}_{\mu}(q^2)v_b(p_b)
\]

Here \(\tilde{\Gamma}_\mu^{\mu}\) has the form eq. (2) with the form factors \(F_{1,2}^{L,R}(q^2)\) replaced by \(\tilde{F}_{1,2}^{L,R}(q^2)\). To lowest order in \(\alpha_s\) the penguin amplitude for the decay process

\[
b\rightarrow q_{\bar{q}}g \rightarrow q_{\bar{q}}q_{\bar{q}} (q_{\bar{q}}q_{\bar{q}})
\]

is

\[
M_{Peng} = -i(\alpha_s/\pi)[\bar{u}_k(p_k)T^a\lambda_{\mu}u_b(p_b)]\times[\bar{v}_k(p_{\bar{q}})\gamma^\mu T^b\nu_{\bar{q}}(p_{\bar{q}})],
\]

where \(\alpha_s = g_s^2/4\pi\) and

\[
\Lambda_{\mu} = \gamma_{\mu}[F_1^L(q^2)P_L + F_1^R(q^2)P_R] + (i\sigma_{\mu\nu}q^{\nu}/q^2)
\]

\[
\times[F_2^L(q^2)P_L + F_2^R(q^2)P_R],
\]

Similarly, for \(b\rightarrow q_{\bar{q}}q'\), the amplitude is

\[
\tilde{M}_{Peng} = i(\alpha_s/\pi)[\bar{u}_k(p_k)T^a\tilde{\lambda}_\mu v_{\bar{q}}(p_{\bar{q}})]
\]

\[
\times[\bar{v}_{\bar{q}}(p_{\bar{q}})\gamma^\mu T^b\nu_{\bar{q}}(p_{\bar{q}})],
\]

where \(\tilde{\lambda}_\mu\) is obtained from eq. (5) by the replacement of all the \(F(q^2)\) form factors by \(\tilde{F}(q^2)\) form factors. The top quark dominates in the sum for \(F_{a}\), hence at value of \(q^2\) (a good approximation), we have \(F_{a}^L(q^2) \approx F_{a}^L(0)\) and \(F_{a}^R(q^2) \approx F_{a}^R(0)\) [3], so
\[ F_1^L(q^2) = \left( \frac{G_F}{\sqrt{2}} \right) \sum_{i=a,c,t} V_{ib}^* V_{ih} f_i(x_i, q^2), \quad F_1^R(0) = 0 \]
\[ F_2^L(0) / m_q = F_2^R(0) / m_b = \left( \frac{G_F}{\sqrt{2}} \right) \sum_{i=a,c,t} V_{ib}^* V_{ih} f_2(x_i), \]

where \( x_i = m_i^2 / M_W^2 \) (\( i = u, c, t \)) and
\[ f_2(x) = -\left( x^2 / 4 \right) \left( 2 + 3/x^2 - 6/x^3 + 3/x^4 + 6 \ln x \right) \]
\[ f_1(x) = \left( 1/12 \right) \left( 1 - x \right)^{4/3} \times \left[ 18x^2 - 29x^3 + 10x^4 + 8x^5 - (8 - 32x + 18x^2) \ln x \right], \]
\[ f_1(x, q^2) = \left( 10/9 \right) - \left( 2/3 \right) \ln x + (2/3z_i) - (2(2z_i + 1)/3z_i) g(z_i). \]

Here \( z_i = q^2 / 4m_i^2 \) and
\[ g(z) = \sqrt{\frac{1 - z}{1 - z}} \arctan\left( \sqrt{\frac{z}{1 - z}} \right), \quad z < 1 \]
\[ g(z) = \frac{1}{2} \ln \left[ \frac{\sqrt{z} + \sqrt{z - 1}}{\sqrt{z} - \sqrt{z - 1}} - \pi i \right], \quad z > 1 \]

For the u quark, \( z_i \) is large and we use the asymptotic form of eq. (11).
\[ f_1(x, q^2) = \left( 10/9 \right) - \left( 2/3 \right) \ln q^2 / M_W^2 - \pi i \]

We find \( F_1^L \gg F_2^R \) and \( F_2^L \gg F_2^L \). For the \( b \to d q \bar{q}' \) amplitude we find that \( F_1^L \) is dominant. Processes like \( b \to s \bar{s} \) and \( b \to d \bar{s} \) are expected to be penguin dominated [4] and \( F_1^L \) dominates all the other form factors. In the \( b \to s \bar{q}' \bar{q}' \) transition, we again find that \( F_1^L \gg F_2^R \), \( F_2^L \gg F_2^L \) and the \( F_1^L \) amplitude to be dominant.

Now, a very important issue is the generation of QCD corrections to penguin operators. Consider, for example, the local operator \( (\bar{q}_a \gamma_\mu q)_v A (\bar{d}_\beta \gamma_\mu \gamma_5 b)_v - A \), which is directly induced by W-boson exchange. In this case, additional QCD correction diagrams, with a gluon contribute and as a consequence four operators, instead of two, are involved in the mixing under renormalization. These are [5, 6]:
\[ Q_3 = (\bar{d}_\beta \gamma_\mu b)_v - A \sum_q (\bar{q}_a \gamma_\mu q)_v - A , \]
\[ Q_4 = (\bar{d}_\beta b)_v - A \sum_q (\bar{q}_a \gamma_\mu q)_v - A , \]
\[ Q_5 = (\bar{d}_\beta b)_v - A \sum_q (\bar{q}_a q)_v + A , \]
\[ Q_6 = (\bar{d}_\beta b)_v - A \sum_q (\bar{q}_a q)_v + A , \]
\[ \alpha \text{ and } \beta \text{ are colour indices. The sum over } q \text{ runs over all quark flavours that exist in the effective theory in} \]

question. Since the gluon coupling is of course flavor conserving, it is clear that penguins cannot be generated from the operator current due to the gluon coupling in the lower part. For convenience, this vector structure is decomposed into a \((V-A)\) and a \((V+A)\) part according to chiral representation,
\[ (\bar{q}_a \gamma_\mu ((1 + \gamma_5) / 2) b)_A \] and
\[ (\bar{q}_a \gamma_\mu ((1 - \gamma_5) / 2) b)_L \]
and in the terms of two component spinors are given by,
\[ \bar{q}_a \gamma_\mu ((1 - \gamma_5) / 2) b)_A = \eta_{ial} \tilde{\sigma}^\mu b_{al} \]
\[ \bar{q}_a \gamma_\mu ((1 + \gamma_5) / 2) b)_L = \eta_{ial} \tilde{\sigma}^\mu b_{al} \]
\[ \bar{q}_a \gamma_\mu ((1 + \gamma_5) / 2) b)_A = \eta_{ial} \tilde{\sigma}^\mu b_{al} \]
\[ \bar{q}_a \gamma_\mu ((1 - \gamma_5) / 2) b)_L = \eta_{ial} \tilde{\sigma}^\mu b_{al} \]

For each of these, two different colour forms arise due to the colour structure of the exchanged gluon. The amplitude (4) can be written [7],
\[ M_{Peng} = -i(G_F / \sqrt{2}) \left[ \alpha_s (M_W / 8 \pi) \right] \]
\[ \times \left[ \sum_{i=a,c} V_{ib} V_{iq}^* f_i(x_i, q^2) + V_{ib}^* V_{iq}^* f_i(x_i) \right] Q_\beta \]
\[ + \left( 1/2 \right) \left[ \sum_{i=a,c} V_{ib} V_{iq}^* f_i(x_i) Q_\beta \right], \]
\[ Q_\beta \text{ is the chromomagnetic dipole operator:} \]
\[ Q_\beta = 4 \alpha_s^2 m_b (\bar{q}_a \gamma_\mu (1 + \gamma_5) T_{\alpha \beta} b \bar{b}) \]
\[ \times (q_\nu / q^2) (\bar{q}_\gamma \gamma^\mu T_{\alpha \beta} q_\nu) , \]
\[ \text{Here} \]
\[ Q_\beta = Q_4 + Q_6 = (1/3) (Q_2 + Q_6) . \]
As a weak decay under the presence of the strong interaction B meson decays require special techniques [8]. The main tool to calculate such B meson decays is the effective Hamiltonian theory [9,10]. It is a two-step process, starting with an operator product expansion (OPE) and performing a renormalization group equation (RGE) analysis afterwards [10,11,12]. The necessary machinery has been developed over the last years.

The derivation starts as follows: If the kinematics of the decay are of the kind that the masses of the internal particle \( M_f \) are much larger than the external momenta \( P \), \( M_f^2 \gg p^2 \), then the heavy particle can be integrated out. This concept takes a concrete form with the functional integral formalism. It means that the heavy particles get removed as dynamical degrees of freedom from the theory hence their fields do not appear in the (effective) Lagrangian anymore. Their residual effect lies in the generated effective vertices [13]. In this way, an effective low energy theory can be constructed from a full theory like the Standard Model [14]. A well known example is the four-Fermi interaction, where the W-boson propagator is made local for \( M_W^2 \gg q^2 \) (q denotes the momentum transfer through the W):
where the ellipses denote terms of higher order in 1/M_W.

Apart from the t quark, the basic framework for weak decays quarks is the effective field theory relevant for scales M_W, M_Z, M_t >> μ [9,15]. This framework, as stated before, brings in local operators, which govern "effectively" the transition in question. From decaying quark point of view, it represents the generalization of the Fermi theory as formulated by Sudershan and Marshak and Feynman and Gell-Mann forty years ago.

It is well known that the decay amplitude is the product of two different parts, whose phases are made of a weak (Cabbibo-Kobayashi-Maskawa) and a strong (final state interaction) contribution. The weak interactions in particular penguins which effectively generate new operators. These are in particular the three categories [16]: 1, 2 current-current operators, 3, 6, 8 gluonic penguin operators and 8, 10 Electroweak penguin operators. Moreover, each operator is multiplied by a calculable Wilson coefficient (Q_μ).

Consequently, the relevant effective Hamiltonian for B-meson decays generally involves several operators Q_μ with various colour and Dirac structures which are different from Q_μ. The operators can be grouped into three categories [16]: i = 1, 2 – current-current operators, i = 3, 6, 8 – gluonic penguin operators and i = 7, 10 – Electroweak penguin operators. Moreover, each operator is multiplied by a calculable Wilson coefficient C_μ (μ):

\[ H_{\text{eff}} = 2\sqrt{2}G_F \sum_{i=1}^{6,8} d_i(\mu) Q_i(\mu) + \sum_{i=7}^{10} d_i(\mu) Q_i(\mu), \]

where the scale μ is discussed below, d_i(μ) = V_{CKM} C_i(μ) and V_{CKM} denotes the relevant CKM factors that are:

\[
\begin{align*}
  d_{1,2} &= V_{tb} V_{\bar{t}b}^* C_{1,2}, \\
  d_{3,6} &= -V_{tb} V_{\bar{t}b}^* C_{3,6}, \\
  d_8 &= -(\alpha_s/4\pi) V_{tb} V_{\bar{t}b}^* C_8, \\
  d_{7,10} &= -(3/2)\alpha_s V_{tb} V_{\bar{t}b}^* C_{7,10}.
\end{align*}
\]

For tree-level the d_{1,2} coefficients are:

\[
\begin{align*}
  d_1 &= V_{tb} V_{\bar{t}b}^*, \\
  d_2 &= 0.
\end{align*}
\]

and for the effective penguin model the d_{3,6,8} coefficients are:

\[
\begin{align*}
  d_3 &= d_5 = (1/6)(\alpha_s/4\pi) \sum_{i=u,d,t} V_{iq}^* V_{ib} f_1(x_i), \\
  d_4 &= d_6 = 3d_3, \\
  d_8 &= -(m_b/2)(\alpha_s/4\pi) \sum_{i=u,d,t} V_{iq}^* V_{ib} f_2(x_i).
\end{align*}
\]

At this stage it should be mentioned that the usual Feynman diagram containing full W propagators, Z^0 propagators and top quark propagators really represent the happening at scales O(M_W) whereas the true picture of a decaying hadron is more correctly described by the local operators in question. Thus, whereas at scale O(M_W), we have to deal with the full six-quark theory containing the photon, weak gauge bosons and gluon, at scale O(1GeV) the relevant effective theory contains only three light quarks u,d, s, gluons and the photon. At intermediate energy scales μ = O(m_b) and μ = O(m_c) relevant for beauty and charm decays, effective five-quark and effective four-quark theories have to be considered, respectively [17].

The usual procedure then is to start at a high energy scale O(M_W) and consecutively integrate out the heavy degrees of freedom (heavy with respect to the relevant scale μ) from explicitly appearing in the theory. The word explicitly is very essential here. The heavy fields did not disappear. Their effects are merely hidden in the effective gauge coupling constants, running masses and most importantly the coefficients describing the effective strength of the operators at a scale μ, the Wilson coefficient functions C_μ (μ) [5,9,10,18]. It is straightforward to apply H_{\text{eff}} to B- and D-meson decays as well by changing the quark flavours appropriately. μ is some low-energy scale of O(1GeV), O(m_c) and O(m_b) for K, D, and B meson decays, respectively. The argument μ of the operators Q_μ(μ) means that their matrix elements are to be normalized at scale μ.

2. Magnetic dipole amplitude of b → q_iq_kq_j

A charge particle in orbital motion generates a magnetic...
dipole moment of a magnitude proportional to its orbital angular momentum. Further more, a particle with intrinsic angular momentum or spin has an intrinsic magnetic moment. The magnetic dipole term in the penguin amplitude, according to eq. (5), is
\[ \Lambda = (i \sigma_{\mu \nu} q^\nu / q^2) [F_2^2(q^2) P_2 + F_2^3(q^2) P_R]. \]  
(29)

Also, according to eq. (8) magnetic (dipole) form factor at \( q^2 = 0 \), \( q^2 / M^2_\gamma \ll 1 \) is
\[ \frac{F_2^2(0)}{m_k} = \frac{F_2^3(0)}{m_b} = \frac{g_2^2}{8M^2_\gamma} \sum_i V_{ib}^* V_{if} f_2(x_i). \]  
(30)

The top quark is dominant for \( F_2^3(0) \), so we can write
\[ F_2^3(0) = m_k (G_F / \sqrt{2}) V_{tb}^* V_{tb} f_2(x_i). \]  
(31)

Here \( f_2(x_i) \) defined by (9) and \( x_i = m_i^2 / M^2_\gamma \), also we saw that \( F_2^2(0) \) << \( F_2^3(0) \), because \( m_k \ll m_b \) so the magnetic dipole term becomes:
\[ \Lambda = (i \sigma_{\mu \nu} q^\nu / q^2) F_2^3(0) P_R. \]  
(32)

Putting in the penguin am really plitude, according to eq. (4),
\[ M^{\text{dip}} = \frac{g_2^2}{4\pi^2} \times [\bar{t}_k(p_k) T^a \sigma_{\mu \nu} q^\nu / q^2 F_2^3(0) P_R u_b(p_b)] \]  
(33)

The magnetic penguin of penguin amplitude is given by (see App.A),
\[ M^{\text{dip}} = A_6 \delta[k_L] \bar{\sigma}_{\mu [b_L]} i L \bar{\sigma}_\mu [J_L] \]  
+ \[ \bar{t}_k(p_k) T^a \sigma_{\mu \nu} q^\nu / q^2 F_2^3(0) P_R u_b(p_b) \]  
(34)

\[ A_6 = (1 / \sqrt{2}) (4 / 3)(m_b / q^2). \]  
(35)

Now we must calculate each terms of the above equation for b spins project -1/2 and 1/2, then squaring these terms and summing up all of them and finally, averaging. The penguin amplitudes of magnetic dipole for b spins project -1/2 and 1/2 are given by (see App.A),
\[ M^{\text{dip}}(1/2) = A_6 \delta[k_L] \bar{\sigma}_{\mu [b_L]} i L \bar{\sigma}_\mu [J_L] \]  
\[ + \bar{t}_k(p_k) T^a \sigma_{\mu \nu} q^\nu / q^2 F_2^3(0) P_R u_b(p_b) \]  
(36)

\[ M^{\text{dip}}(-1/2) = A_6 \delta[k_L] \bar{\sigma}_{\mu [b_L]} i L \bar{\sigma}_\mu [J_L] \]  
\[ + \bar{t}_k(p_k) T^a \sigma_{\mu \nu} q^\nu / q^2 F_2^3(0) P_R u_b(p_b) \]  
(37)

3. 3. Effective Hamiltonian decay rates of \( b \rightarrow q_1 q_2 \bar{q}_j \)

The effective \( \Delta B = 1 \) Hamiltonian at scale \( \mu = O(m_b) \) for tree plus penguin and including the electroweak penguin and the magnetic dipole term is [5,6,9],
\[ H^{\text{eff}}_{\Delta B = 1} = 2 \sqrt{2} G_F \{ [\bar{q}_1(1) Q_1^1(1) + d_{2c}(\mu) Q_2^2(\mu)] \]  
\[ + [d_{1b}(\mu) Q_1^1(\mu) + d_{2s}(\mu) Q_2^2(\mu)] \]  
\[ + \sum_{i=3}^{6,8} d_i(\mu) Q_i(\mu) + \sum_{i=7}^{10} d_i(\mu) Q_i(\mu) \}. \]  
(38)

Here \( d_1, d_2, ..., d_7, d_8 \) are defined by (26),\( d_{1b,2c} = d_{1b,2c} (i = c, u) \) and index \( k \) refer to d or s. The decay rate is given by (see App.B)
\[ d^2 \Gamma_{Q_1 \cdots Q_6} / dxdy = \Gamma_{0b} I_{ps}^{EH}, \]  
(39)

\[ I_{ps}^{1/2} = \alpha_1 I_{ps}^{1/2} + \alpha_2 I_{ps}^{1/2} + \alpha_3 I_{ps}^{1/2}, \]  
(40)

\[ \Gamma_{0b} = \frac{6 \alpha_1 f_{ab}(1 - h_{abc})}{\alpha_1 f_{ab} - h_{abc}} , \]  
(41)

\[ d_1 = d_2 + d_3 + d_4^2 + 2d_4^2 + 2d_3^2 + d_5^2 + 2d_6^2 , \]  
(42)

\[ d_2 = d_5^2 + 2d_5^2 + 2d_6^2 , \]  
(43)

\[ d_3 = \text{Re} \{ (3d_3 + d_4 + d_4 + 3d_4) d_6^* \} + (d_1 + 3d_2 + 3d_4 + d_4) d_6^* \} . \]  
(44)

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\[ H^{\text{eff}}_{\Delta B = 1} = 2 \sqrt{2} G_F \{ [\bar{q}_1(1) Q_1^1(1) + d_{2c}(\mu) Q_2^2(\mu)] \]  
\[ + [d_{1b}(\mu) Q_1^1(\mu) + d_{2s}(\mu) Q_2^2(\mu)] \]  
\[ + \sum_{i=3}^{6,8} d_i(\mu) Q_i(\mu) + \sum_{i=7}^{10} d_i(\mu) Q_i(\mu) \}. \]  
(38)

Here \( d_1, d_2, ..., d_7, d_8 \) are defined by (26),\( d_{1b,2c} = d_{1b,2c} (i = c, u) \) and index \( k \) refer to d or s. The decay rate is given by (see App.B)
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(39)

\[ I_{ps}^{1/2} = \alpha_1 I_{ps}^{1/2} + \alpha_2 I_{ps}^{1/2} + \alpha_3 I_{ps}^{1/2}, \]  
(40)

\[ \Gamma_{0b} = \frac{6 \alpha_1 f_{ab}(1 - h_{abc})}{\alpha_1 f_{ab} - h_{abc}} , \]  
(41)

\[ d_1 = d_2 + d_3 + d_4^2 + 2d_4^2 + 2d_3^2 + d_5^2 + 2d_6^2 , \]  
(42)

\[ d_2 = d_5^2 + 2d_5^2 + 2d_6^2 , \]  
(43)

\[ d_3 = \text{Re} \{ (3d_3 + d_4 + d_4 + 3d_4) d_6^* \} + (d_1 + 3d_2 + 3d_4 + d_4) d_6^* \} . \]  
(44)
4. Effective Hamiltonian of electroweak penguin decay rates

The generalization of the $\Delta B=1$ Hamiltonian in pure QCD to incorporate electroweak penguin operators is the sum of the $Q_3,...,Q_6, Q'_3,...,Q'_6$ eq. (38). The $\Delta B=1$ Wilson coefficients for $Q_3^{\mu},Q_3^{\nu},Q_3^{\alpha},Q_3^{\beta},Q_3^{\gamma},Q_3^{\delta}$, $O_3,...,O_6$ in the mixed case of QCD and QED. Therefore the discussion of $C_1,...,C_6$ is also valid for the present case. It was observed that, all of the terms $Q_1, Q_2, Q_3, Q_4$ had a form Left-Left handed. Terms $Q_5, Q_6$ have a form a Right-Left handed, terms $Q_7, Q_8$ have a form a Right-Right handed, terms $Q_9, Q_10$ have a form a Left-Right handed, and terms $Q_9, Q_10$ have a form a Right-Left handed. Therefore terms $Q_9, Q_10$ have a form a Left-Right handed, and terms $Q_9, Q_10$ have a form a Right-Left handed. Thus the partial decay rate including electroweak penguin is the same as eq. (39) with different constants $\alpha_1, \alpha_2$ and $\alpha_3$.

\[
\alpha_1 = |d_1 + d_2 + d_3 + d_4 + d_5 + d_6|^2
\]

\[+ 2|d_1 + d_2 + d_3 + d_4 + d_5 + d_6|^2 + 2|d_2 + d_3 + d_4 + d_5 + d_6|^2, \]

\[
\alpha_2 = |d_5 + d_6 + d_7 + d_8|^2 + 2|d_5 + d_6|^2 + 2|d_6 + d_7|^2 + 2|d_5 + d_6 + d_7|^2, \]

\[
\alpha_3 = \text{Re}(3d_1 + d_2 + d_3 + 3d_4 + d_5 + 3d_6)(d_5^* + d_6^*), \]

\[+(d_1 + d_3 + d_4 + d_3 + d_4 + d_3)(d_5^* + d_6^*)|j_{\mu}|L + |\bar{\sigma}_{\mu}|j_{\mu}|L, \quad (45)\]

where $d_1,...,d_6,d_7,...,d_{10}$ defined by eq. (26) and $\epsilon_q$ is the quark electric charge which is given by $\epsilon_{d,s,t} = 2/3$, $\epsilon_{d,s,t} = -(1/3)$. (46)

5. Effective Hamiltonian of magnetic dipole decay rates

Now the aim is to calculate the decay rates of $b \to q_d q_d \bar{q}_j$ according to the effective Hamiltonian ($Q_1,...,Q_6$), including magnetic dipole ($Q_3$) terms. We obtained the amplitude of operators $Q_1,...,Q_6$, and the amplitude of magnetic dipole ($Q_3$) terms. Adding the amplitudes, we calculated the decay rates of operators of the effective Hamiltonian including magnetic dipole terms ($Q_1,...,Q_6,Q_3$). The amplitude of the effective Hamiltonian including magnetic dipole is given by (see App.C)

\[
|M_{\text{spin-ave}}^{\text{tot}}|^2 = \frac{1}{4}[(g_1 - 2v_k v_i (g_4 - g_5) \cos \theta - \theta_k) + g_2 + 2v_k v_i (g_4 + g_7) \cos \theta - \theta_k - 2\sqrt{1 - v_i^2} \sqrt{1 - v_i^2} g_3]
\]

\[+ 2v_k v_i (g_4 - g_5) \cos \theta - \theta_k], \quad (47)\]

In order to check the above equation, one can obtain the amplitude of tree-level and the effective Hamiltonian ($Q_1,...,Q_6$). The amplitude of tree-level ($d_2 = d_3 = d_4 = d_5 = d_6 = d_8 = 0$) is given by

\[
|M_{\text{spin-ave,TL}}^{\text{tot}}|^2 = \frac{1}{4}[(h_i^2/2) - 2h_i^2 v_k \cos \theta - \theta_k + 0 + 0]
\]

\[+ (h_i^2/2)[1 + v_i v_k \cos \theta - \theta_k] - (\sqrt{1 - v_i^2})^2/(4h_i h_2)], \quad (48)\]

The differential of decay rate of the effective Hamiltonian plus magnetic dipole eq. (47) is given by

\[
d^2\Gamma = \frac{G_F^2 M_b^2}{192\pi^3} \frac{1}{2} (I_1 + I_2 + I_3), \quad (50)\]

where

\[
I_1 = 6xy_{ab}[g_1 - 2(g_4 - g_5)h_{abc}], \quad I_2 = 6xy_{bc}[g_2 + 2g_6 + g_7]h_{cab}], \quad I_3 = 6xy_{ac}[-2g_3h_{ab}h_{yc} - (g_4 - g_5)h_{abc}] \quad (51)\]

and $f_{ab},f_{bc},f_{ac},h_{abc},h_{cab},h_{acb},h_{abc},h_{abc},h_{abc}$ defined by (B-16). Now the decay rates of eq. (50) is checked for Tree-Level and effective Hamiltonian ($Q_1,...,Q_6$). Putting $d_2 = d_3 = d_4 = d_5 = d_6 = d_8 = 0$ in eq. (50) the decay rate of Tree-Level is obtained which is the same as eq. (43) and putting $d_8 = 0$ in eq. (33) the decay rate of the effective Hamiltonian is found to be the same as eq. (39).

6. Effective Hamiltonian of electroweak penguin and magnetic dipole decay rates

The partial decay rate of the effective Hamiltonian plus Magnetic Dipole was given by eq. (50). Now the partial decay rate including electroweak penguin is obtained. In this case, the electroweak penguin operators ($d_7,d_8,d_9,d_{10}$) should be included in the as did before for obtaining the partial decay rate is given by

\[
d^2\Gamma = \frac{G_F^2 M_b^2}{192\pi^3} \frac{1}{2} (I_1 + I_2 + I_3), \quad (52)\]

where $I_1,I_2,I_3$ defined by eq. (51) and $h_1,h_2,h_3$ defined by,
Table 1. Effective Wilson coefficients $C_i^{\text{eff}}$ at the renormalization scale $\mu = 2.5$ GeV for the various $b \rightarrow q$ ($\bar{b} \rightarrow \bar{q}$) transitions.

<table>
<thead>
<tr>
<th>Process</th>
<th>$b \rightarrow d$</th>
<th>$\bar{b} \rightarrow \bar{d}$</th>
<th>$b \rightarrow s$</th>
<th>$\bar{b} \rightarrow \bar{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1^{\text{eff}}$</td>
<td>1.1679 + 0.0000i</td>
<td>1.1679 + 0.0000i</td>
<td>1.1679 + 0.0000i</td>
<td>1.1679 + 0.0000i</td>
</tr>
<tr>
<td>$C_2^{\text{eff}}$</td>
<td>-0.3525 + 0.0000i</td>
<td>-0.3525 + 0.0000i</td>
<td>-0.3525 + 0.0000i</td>
<td>-0.3525 + 0.0000i</td>
</tr>
<tr>
<td>$C_3^{\text{eff}}$</td>
<td>0.0217 + 0.0018i</td>
<td>0.0217 + 0.0047i</td>
<td>0.0217 + 0.0030i</td>
<td>0.0217 + 0.0029i</td>
</tr>
<tr>
<td>$C_4^{\text{eff}}$</td>
<td>-0.0498 - 0.0054i</td>
<td>-0.0535 - 0.0142i</td>
<td>-0.0531 - 0.0086i</td>
<td>-0.0531 - 0.0086i</td>
</tr>
<tr>
<td>$C_5^{\text{eff}}$</td>
<td>0.0156 + 0.0018i</td>
<td>0.0173 + 0.0047i</td>
<td>0.0170 + 0.0029i</td>
<td>0.0170 + 0.0029i</td>
</tr>
<tr>
<td>$C_6^{\text{eff}}$</td>
<td>-0.0625 - 0.0054i</td>
<td>-0.0678 - 0.0142i</td>
<td>-0.0667 - 0.0086i</td>
<td>-0.0667 - 0.0086i</td>
</tr>
</tbody>
</table>

Table 2. Branching ratios (BR) of tree-level $b \rightarrow q+q\bar{q}$ (43) ($\Gamma_{tot} = 3.0457 \times 10^{-13}$ GeV).

<table>
<thead>
<tr>
<th>Process</th>
<th>$BR \times 10^{-2}$</th>
<th>Process</th>
<th>$BR \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow ce^{-}\bar{\nu}_e$</td>
<td>14.62</td>
<td>$b \rightarrow ue^{-}\bar{\nu}_e$</td>
<td>0.231</td>
</tr>
<tr>
<td>$b \rightarrow c\mu^{-}\bar{\nu}_\mu$</td>
<td>14.62</td>
<td>$b \rightarrow u\mu^{-}\bar{\nu}_\mu$</td>
<td>0.231</td>
</tr>
<tr>
<td>$b \rightarrow ct^{-}\bar{\nu}_t$</td>
<td>0.714</td>
<td>$b \rightarrow u\tau^{-}\bar{\nu}_\tau$</td>
<td>0.084</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{d}\bar{u}$</td>
<td>49.02</td>
<td>$b \rightarrow u\bar{d}\bar{u}$</td>
<td>0.725</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{s}\bar{c}$</td>
<td>16.13</td>
<td>$b \rightarrow u\bar{s}\bar{c}$</td>
<td>0.019</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{s}\bar{c}$</td>
<td>0.857</td>
<td>$b \rightarrow u\bar{s}\bar{u}$</td>
<td>0.531</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{s}\bar{u}$</td>
<td>2.352</td>
<td>$b \rightarrow u\bar{s}\bar{u}$</td>
<td>0.355</td>
</tr>
</tbody>
</table>

7. Numerical results

As an example of the use of the above formalism, we use the standard Particle Data Group [19] parameterization of the CKM matrix with the central values $\theta_{12} = 0.221$, $\theta_{13} = 0.0035$, $\theta_{23} = 0.041$, and choose the CKM phase $\delta_{13}$ to be $\pi/2$. Following Ali and Greub [16], we treat internal quark masses in tree-level loops with the values (GeV) $m_b = 4.88$, $m_s = 0.2$, $m_d = 0.01$, $m_u = 0.005$, $m_c = 1.5$, $m_t = 0.0005$, $m_\mu = 0.1$, $m_\tau = 1.777$ and $m_\nu_e = m_\nu_\mu = m_\nu_\tau = 0$. The effective Wilson coefficients $C_i^{\text{eff}}$ at the renormalization scale $\mu = 2.5$ GeV for the various $b \rightarrow q$ ($\bar{b} \rightarrow \bar{q}$) transitions, shown in the Table 1 [7]. Also, following H.Y. Cheng [20], [21,5,10] and [22, 23, 5, 10], we choose the effective Wilson coefficients of $C_7^{\text{eff}} - C_{10}^{\text{eff}}$, $C_{11}^{\text{eff}} = -(0.0276 + i0.0369)\alpha_e$, $C_{12}^{\text{eff}} = 0.054\alpha_e$, $C_{13}^{\text{eff}} = -(1.138 + i0.0369)\alpha_e$, $C_{14}^{\text{eff}} = 0.263\alpha_e$, here $\alpha_e = 1/137$, that is the electromagnetic coupling constant. In order to obtain the total rates at the tree-level a sum is made over the $b$-quark decay rates. The total decay rate and branching ratios of several of semileptonic and hadronic modes are given in Table 2. We see that the modes $b \rightarrow clv$, $b \rightarrow cd\bar{u}$ and $b \rightarrow cs\bar{c}$ are dominant. The total $b$-quark decay rate at the tree-level is given by

$$\Gamma_{\text{tot}} = \Gamma_{\text{Semileptonic}} + \Gamma_{\text{Hadronic}} = 3.0457 \times 10^{-13} \text{GeV}. $$

It is observed that the decay rate for the antiparticle $\bar{b} \rightarrow \bar{u}\bar{d}u$ is greater than the particle decay rate $b \rightarrow u\bar{d}u$, and the antiparticle decay rate $\bar{b} \rightarrow \bar{c}s\bar{c}$ is less than the particle decay rate $b \rightarrow cs\bar{c}$, and so on. We consider that the modes $b \rightarrow cd\bar{u}$, and $b \rightarrow cs\bar{c}$ are dominant.

The branching ratios of the effective Hamiltonian $(Q_1, \ldots, Q_6)$ for particles and antiparticles are collected in Table 3. In this case modes $b \rightarrow cd\bar{u}$ and $b \rightarrow cs\bar{c}$ are dominant. Also, the branching ratios including the
Table 3. Branching ratios ($BR \times 10^{-3}$) of tree-level ($T$) eq. (43), Effective Hamiltonian ($EH$) eq. (39), Effective Hamiltonian including Electroweak Penguin ($EH + EP$) eq. (45), Effective Hamiltonian including Magnetic Dipole ($EH + MD$) eq. (50) and Effective Hamiltonian including Electroweak Penguin and Magnetic Dipole ($EH + EP + MD$) eq. (52) of the particles and antiparticles for the various $b \rightarrow q$ ($\bar{b} \rightarrow \bar{q}$) transitions. The total decay rates are in unit of $10^{-13}$ GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\Gamma_{tot}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow u\bar{d}u$</td>
<td>0.725</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{d}c$</td>
<td>0.857</td>
</tr>
<tr>
<td>$b \rightarrow c\bar{d}u$</td>
<td>49.02</td>
</tr>
<tr>
<td>$b \rightarrow u\bar{d}c$</td>
<td>0.019</td>
</tr>
<tr>
<td>$b \rightarrow us\bar{u}$</td>
<td>0.531</td>
</tr>
<tr>
<td>$b \rightarrow cs\bar{c}$</td>
<td>0.355</td>
</tr>
<tr>
<td>$b \rightarrow cs\bar{u}$</td>
<td>2.352</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{u}\bar{d}u$</td>
<td>0.725</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{c}\bar{d}c$</td>
<td>0.857</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{c}\bar{d}u$</td>
<td>49.02</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{u}\bar{d}c$</td>
<td>0.019</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{u}\bar{s}u$</td>
<td>0.531</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{c}\bar{s}c$</td>
<td>16.13</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{u}\bar{s}c$</td>
<td>0.355</td>
</tr>
<tr>
<td>$\bar{b} \rightarrow \bar{c}\bar{s}u$</td>
<td>2.352</td>
</tr>
</tbody>
</table>

The branching ratios of the effective Hamiltonian plus magnetic dipole, and the effective Hamiltonian plus electroweak Penguin plus magnetic dipole are shown as well as those of the pure Penguin are given in Table 3 and 4 respectively. It is seen that, in the pure Penguin decays, modes $b \rightarrow s\bar{s}\bar{s}$ and $b \rightarrow s\bar{d}\bar{d}$ are dominant. Also, it is observed that, terms of Current-Current plus Penguin operators dominate as compared with the electroweak Penguin operators.

The branching ratios of the effective Hamiltonian plus magnetic dipole, and the effective Hamiltonian plus electroweak Penguin plus magnetic dipole are shown in Table 3 as well. It shows that the electroweak Penguin plus magnetic dipole term is small and can be neglected in the total decay rate. The total decay rate of the effective Hamiltonian ($Q_1, ..., Q_6$) of particle and antiparticle are given by

$$\Gamma_{tot}^{EH} (Q_1, ..., Q_6) = 3.404 \times 10^{-13} \text{ GeV},$$

In addition, the total decay rate of particles and antiparticles including electroweak Penguin ($Q_1, ..., Q_6, Q'_7, ..., Q'_{10}$) for $b$-quark decays are given by

$$\Gamma_{tot}^{EH+EP} (Q_1, ..., Q_{10}) = 3.497 \times 10^{-13} \text{ GeV}.$$
Table 4. Branching ratios of pure penguin of effective Hamiltonian of the particles and antiparticles for the various $b \to q ~(\overline{b} \to \overline{q})$ transitions (44). ($\Gamma_{\text{tot}} = 3.404 \times 10^{13}\text{GeV}$).

<table>
<thead>
<tr>
<th>Process</th>
<th>$BR \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to d\overline{d}d$</td>
<td>2.408</td>
</tr>
<tr>
<td>$b \to d\overline{s}s$</td>
<td>2.687</td>
</tr>
<tr>
<td>$b \to s\overline{d}d$</td>
<td>53.782</td>
</tr>
<tr>
<td>$b \to s\overline{s}s$</td>
<td>54.157</td>
</tr>
</tbody>
</table>

According to Table 2, the dominant mode in b-quark in the semileptonic and hadronic decays are, $b \to c\ell^-\overline{\nu}_\ell$ ($\ell = e, \mu$) and $b \to c\ell\overline{\nu}$ respectively because the decay rates of $b \to c$ channel are very much bigger than those of $b \to u, s$ since $V_{cb} \gg V_{ub}$. In addition, the dominant mode in the pure penguin decays is, $b \to s$. According to Table 4, the branching ratios of pure penguin of the effective Hamiltonian of the particles and antiparticles are close.

The electroweak penguin and magnetic dipole terms are small for b-quark decay rates (electroweak corrections and the magnetic dipole contributions are small) and the decay rate of the tree, effective Hamiltonian, effective Hamiltonian including electroweak penguin, effective Hamiltonian including magnetic dipole and the effective Hamiltonian including electroweak penguin and magnetic dipole of the particles and antiparticles are close. For example, $\Gamma_{b \to s\overline{d}d} > \Gamma_{\overline{b} \to \overline{s}\overline{s}s}$, because the total decay rates of $b -$ and $\overline{b} -$ quark at the tree-level are exactly the same, but in the pure penguin, effective Hamiltonian, effective Hamiltonian including electroweak penguin and magnetic dipole, effective Hamiltonian including electroweak penguin and magnetic dipole of the particles and antiparticles are not very different (see Table 3). The decay rates of $b -$ and $\overline{b} -$ quark at the tree-level are exactly the same, but in the pure penguin, effective Hamiltonian, effective Hamiltonian including electroweak penguin and magnetic dipole, effective Hamiltonian including electroweak penguin and magnetic dipole, are different. For example, $\Gamma_{b \to s\overline{d}d} < \Gamma_{\overline{b} \to \overline{s}\overline{s}s}$, $\Gamma_{b \to s\overline{d}d} < \Gamma_{\overline{b} \to \overline{s}\overline{s}s}$, $\Gamma_{b \to u\overline{d}d} > \Gamma_{\overline{b} \to \overline{u}\overline{u}u}$ and $\Gamma_{b \to s\overline{d}d} \approx \Gamma_{\overline{b} \to \overline{s}\overline{s}s}$, because the total decay rates of $b -$ and $\overline{b} -$ quark must be equal, $\Gamma_{b \to \text{total}} = \Gamma_{\overline{b} \to \text{total}}$.

Also, the decay rates and branching ratios are very similar in all the models but the effective Hamiltonian including electroweak penguin and magnetic dipole total decay rate is about 10% larger than the simple tree or effective Hamiltonian. On the other hand, including the penguin term induced matter antimatter asymmetries. These are largest in the rare decays $b \to u\overline{d}d$; the decay rate of which, is about 7% smaller than that of $\overline{b} \to \overline{s}\overline{u}u$. Also the rate $b \to s\overline{u}u$ is larger than the rate $\overline{b} \to \overline{s}\overline{u}u$.

Appendix A

Penguin amplitude of magnetic dipole

According to eq. (4) the penguin amplitude is given by

$$M^{\text{dip}} = \frac{G_F^2}{8\pi^2} F_2^R (0) (T^a T^a) \times \left[ (\overline{u}_k (p_k) T^a (i\sigma_{\mu\nu} q^\nu / q^2) F_2^R (0) P_R u_b (p_b) ) \times [\overline{v}_i (p_i) \gamma^\mu T^a v_j (p_j) ] \right],$$

(A-1)

where

$$\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu] = \frac{i}{2} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu),$$

and

$$\gamma^\mu \gamma^\nu = \begin{pmatrix} 0 & \sigma^\mu \\ \sigma^\nu & 0 \end{pmatrix} - \begin{pmatrix} \sigma^\mu \sigma^\nu - \sigma^\nu \sigma^\mu \\ 0 \end{pmatrix}. \quad \text{(A-3)}$$

So

$$\sigma^{\mu\nu} = \frac{i}{2} \begin{pmatrix} \sigma^\mu \sigma^\nu - \sigma^\nu \sigma^\mu \\ 0 \end{pmatrix} - \begin{pmatrix} \sigma^\mu \sigma^\nu - \sigma^\nu \sigma^\mu \\ 0 \end{pmatrix}. \quad \text{(A-5)}$$

The wave functions of $b$ and $q_k$ are given by

$$\begin{pmatrix} \psi_{kL} \\ \psi_{kR} \end{pmatrix} = \begin{pmatrix} \sigma^\mu \sigma^\nu - \sigma^\nu \sigma^\mu \\ 0 \end{pmatrix} = \frac{i}{2} \begin{pmatrix} \sigma^\mu \sigma^\nu - \sigma^\nu \sigma^\mu \\ 0 \end{pmatrix} \psi_{bR}. \quad \text{(A-6)}$$

Putting in the penguin amplitude

$$M^{\text{dip}} = \frac{G_F^2}{8\pi^2} F_2^R (0) (T^a T^a) \times \left[ (\overline{u}_k (p_k) T^a (i\sigma_{\mu\nu} q^\nu / q^2) F_2^R (0) P_R u_b (p_b) ) \times [\overline{v}_i (p_i) \gamma^\mu T^a v_j (p_j) ] \right],$$

(A-7)

Putting $q^\nu = (p_b - p_k)^\nu$ in the above equation,

$$M^{\text{dip}} = \frac{G_F^2}{8\pi^2} F_2^R (0) (T^a T^a) \times \left[ (\overline{u}_k (p_k) T^a (i\sigma_{\mu\nu} (p_b - p_k)^\nu) F_2^R (0) P_R u_b (p_b) ) \times [\overline{v}_i (p_i) \gamma^\mu T^a v_j (p_j) ] \right].$$

(A-8)
\[ M^{\text{dip}} = -\frac{g_s^2}{8\pi^2} F_{\mu}^R (0)(T^a T^a) \left\{ \left( k_L | \bar{\sigma}_\mu (p_L^b - \sigma v p_L^b) | b_R \right) \right. \\
\left. - \langle k_L | (\bar{\sigma}_{\mu} p_L^b - \sigma v p_L^b) \sigma_{\mu} | b_R \rangle \right\} \times \frac{1}{q^2} \left( m_b \langle k_L | \bar{\sigma}_\mu | b_R \rangle + m_b \langle k_R | \sigma_{\mu} | b_R \rangle \right) \\
- \langle p_b + p_k \rangle \mu \left\{ \langle k_L | \bar{\sigma}_\mu | b_R \rangle \right\} \times \frac{1}{q^2} \left( m_b \langle k_L | \bar{\sigma}_\mu | b_R \rangle + m_b \langle k_R | \sigma_{\mu} | b_R \rangle \right) \\
- \langle p_b + p_k \rangle \mu \left\{ \langle k_L | \bar{\sigma}_\mu | b_R \rangle \right\} \times \frac{1}{q^2} \left( m_b \langle k_L | \bar{\sigma}_\mu | b_R \rangle + m_b \langle k_R | \sigma_{\mu} | b_R \rangle \right). \]  

\[ (T^a T^a) = 4/3, \]
\[ d_k = -\frac{g_s^2}{8\pi^2} F_{\mu}^R (0) = -\frac{g_s^2}{8\pi^2} m_b \frac{g_s^2}{8\pi^2} \sum_i V_{ib}^a V_{fb}^a (x_i), \] 
\[ = -2(2G_F)(m_b / 2)(\alpha_s / 4\pi) \sum_i V_{ib}^a V_{fb}^a (x_i). \]

So, the magnetic dipole of penguin amplitude is given by:
\[ M^{\text{dip}} = (4/3)d_k (m_b / q^2) \left\{ \langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle \right\} \\
+ \langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle - 2\langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle. \]

The b quark is at rest and to have spin projection –1/2 along angle \( \theta_b \), thus the spin projection of b quark of +1/2 is along \( \theta_b - \pi \). 

b spin(–1/2) and angle \( \theta_b \propto (1/\sqrt{2}) \left( -\sin(\theta_b / 2) \right) \]

b spin(+1/2) and angle \( \theta_b \propto (1/\sqrt{2}) \left( \cos(\theta_b / 2) \right) \).

Putting the factor of \((1/\sqrt{2})\) in the \( M^{\text{dip}} \) and neglecting the terms \( \langle k_L | b_R \rangle \), thus the amplitude of magnetic dipole becomes
\[ M^{\text{dip}} = A_b d_k (m_b / q^2) \left\{ \langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle \right\} \\
+ \langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle, \]

\[ A_b = (1/\sqrt{2})(4/3)(m_b / q^2). \]

Terms \( \langle \bar{\sigma}_\mu | \sigma_{\mu} \rangle_{LR} \) for spin +1/2 and –1/2 are obtained by the matrix elements of \( L - L \) hand ed and \( L - R \) hand ed for the b quark
\[ \langle \bar{\sigma}_\mu | \sigma_{\mu} \rangle_{LR} = \sin((\theta_b - \theta_j - \theta_j) / 2) + \sin((\theta_b + \theta_j - \theta_j) / 2), \]
\[ \langle \bar{\sigma}_\mu | \sigma_{\mu} \rangle_{LR} = \cos((\theta_b - \theta_j - \theta_j) / 2) - \cos((\theta_b + \theta_j - \theta_j) / 2), \]

when dealing with penguin amplitudes, the following matrix elements are needed
\[ \langle \bar{\sigma}_\mu | \sigma_{\mu} \rangle_{LR} = \sin((\theta_i - \theta_k - \theta_j) / 2) - \sin((\theta_i + \theta_k - \theta_j) / 2), \]
\[ \langle \bar{\sigma}_\mu | \sigma_{\mu} \rangle_{LR} = \cos((\theta_i - \theta_k - \theta_j) / 2) + \cos((\theta_i + \theta_k - \theta_j) / 2). \]

The first term of (A-20) for b spin project –1/2, according to Fierz transformation,
\[ \langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle = -\langle k_L | \bar{\sigma}_\mu | b_L \rangle \langle \bar{\sigma}_\mu | j_L \rangle. \]
is given by
\[ M_{\alpha}^{\text{dip}}(\pm 1/2) = - A_9 d_8 \left\langle k_L | \hat{\sigma}^{\mu} | h_L \right\rangle \left\langle i_L | \hat{\sigma}_\mu | j_L \right\rangle = A_9 d_8 \left[ - \cos((\theta_0 - \theta_1 - \theta_k + \theta_j) / 2) \right] \] (A-25)
And the first term for b spin project +1/2 is given by
\[ M_{\alpha}^{\text{dip}}(1/2) = - A_9 d_8 \left\langle k_L | \hat{\sigma}^{\mu} | b_L \right\rangle \left\langle i_L | \hat{\sigma}_\mu | j_L \right\rangle = A_9 d_8 \left[ - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2) \right]. \] (A-26)
Also the second term of (A-20) for b spin projection +1/2 is given by
\[ M_{\alpha}^{\text{dip}}(1/2) = - A_9 d_8 \left\langle k_L | \hat{\sigma}^{\mu} | b_L \right\rangle \left\langle i_R | \hat{\sigma}_\mu | j_R \right\rangle = A_9 d_8 \left[ - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2) \right]. \] (A-27)
In addition, the second term for b spin projection +1/2 is given by
\[ M_{\alpha}^{\text{dip}}(1/2) = - A_9 d_8 \left\langle k_L | \hat{\sigma}^{\mu} | b_L \right\rangle \left\langle i_R | \hat{\sigma}_\mu | j_R \right\rangle = A_9 d_8 \left[ - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2) \right] + \sin((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2). \] (A-28)
So the penguin amplitudes of magnetic dipole for b spins project -1/2 and 1/2 are given by
\[ M_{\alpha}^{\text{dip}}(\pm 1/2) = A_9 d_8 \left[ - \sin((\theta_0 + \theta_1 - \theta_k - \theta_j) / 2) \right] + \sin((\theta_0 + \theta_1 - \theta_k - \theta_j) / 2). \] (A-29)
\[ M_{\alpha}^{\text{dip}}(1/2) = A_9 d_8 \left[ - \sin((\theta_0 + \theta_1 - \theta_k + \theta_j) / 2) \right] - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2)] - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2)] + \sin((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2)] + \sin((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2)] - \cos((\theta_0 - \theta_1 + \theta_k - \theta_j) / 2)]. \] (A-30)

**Appendix B**

**Decay rate of the effective Hamiltonian**

The effective $\Delta B = 1$ Hamiltonian at scale $\mu = O(m_t)$ for tree plus penguin and including the electroweak penguin and the magnetic dipole term is given by
\[ H_{\Delta B = 1}^{\text{eff}} = 2 \sqrt{2} G_F \left[ d_{16}(\mu) Q_1^T(\mu) + d_{24}(\mu) Q_2^T(\mu) \right. \]
\[ + \left. d_{1}^T(\mu) Q_1(\mu) + d_{2}^T(\mu) Q_2(\mu) \right] \]
\[ - \sum_{i=3}^{10} \sum_{j=3}^{10} d_i(\mu) Q_i(\mu) + \sum_{i=7}^{10} d_i(\mu) Q_i(\mu) \right], \] (B-1)
where $d_1, \ldots, d_6, d_7, \ldots, d_{10}$ are defined by eq. (26), $d_{12, c u} = d_{42}(\mu = j = c, u)$ and index $k$ refer to d or s. Using (A-22) and (A-23) one can obtain the matrix elements of the effective Hamiltonian operators. In the first step, the tree plus penguin operators $(Q_1, \ldots, Q_6)$ are chosen. All of the terms $Q_1, Q_2, Q_3, Q_4$ have a form L-L handed but terms $Q_1, Q_2$ have a form $\left\langle l_L | \hat{\sigma}^{\mu} | b_L \right\rangle \left\langle k_L | \hat{\sigma}_\mu | j_L \right\rangle$ and terms $Q_3, Q_4$ have a form $\left\langle k_L | \hat{\sigma}^{\mu} | l_L \right\rangle \left\langle i_L | \hat{\sigma}_\mu | j_L \right\rangle$. Consider $i, k$ and $j$ momenta in $\mathbf{XZ}$ plane, so according to (A-22), for the $Q_1, Q_2$ and, we can write for b spin projection 1/2 and −1/2. Also terms $Q_3, Q_4$ differ only by a minus, because $\sin((\theta_0 + \theta_j - \theta_k) / 2) = - \sin((\theta_0 - \theta_j - \theta_k) / 2)$, $\sin((\theta_0 - \theta_j - \theta_k) / 2) = - \sin((\theta_0 + \theta_j - \theta_k) / 2)$.

Terms $Q_5, Q_6$ are of the form L-R handed, $\left\langle i_L | \hat{\sigma}^{\mu} | l_L \right\rangle \left\langle k_R | \hat{\sigma}_\mu | j_R \right\rangle$. The main forms of the terms $Q_5, Q_6$ are $\left\langle k_L | \hat{\sigma}^{\mu} | l_L \right\rangle \left\langle i_R | \hat{\sigma}_\mu | j_R \right\rangle$. These terms can be written according to (A-23). So, the matrix element for b quark spin project 1/2 is given by
\[ M_{\text{eff}} = 2 \sqrt{2} G_F \left[ A_1 + A_2 \right] \left[ \sin((\theta_0 - \theta_j - \theta_k) / 2) \right] + \sin((\theta_k + \theta_j - \theta_k) / 2)] - A_1 \left[ \sin((\theta_0 - \theta_j - \theta_k) / 2) \right] - \sin((\theta_0 + \theta_j - \theta_k) / 2)]. \] (B-3)
here $A_1, A_2$ and $A_3$ are combination of Wilson coefficients and colour factors. The forms of $(\hat{\sigma}^{\mu})^T(\hat{\sigma}_\mu)_{LL}$ and $(\hat{\sigma}^{\mu})(\hat{\sigma}_\mu)_{LR}$ are according to (A-22) and (A-23) respectively. So the square of spin average term $Q_1, \ldots, Q_6$ is given by
\[ [(\hat{\sigma}^{\mu})^T(\hat{\sigma}_\mu)]_{LL} + ([\hat{\sigma}^{\mu})(\hat{\sigma}_\mu)]_{LR}^2 \]
\[ = \alpha_1 (1/16)(1 + v_1)(1 + v_2)(1 + v_3) \left[ 1 - \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ + \alpha_2 (1/16)(1 + v_1)(1 + v_2)(1 + v_3) \left[ 1 + \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ + \alpha_3 (1/16)(1 + v_1)(1 + v_2)(1 + v_3) \left[ 1 + \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ - \cos(\theta_0 - \theta_k - \theta_j). \] (B-4)
Now, one must obtain all of the helicity states for $Q_1, \ldots, Q_6$ and then sum them all. Adding eight terms of helicity states, on finds
\[ [(\hat{\sigma}^{\mu})^T(\hat{\sigma}_\mu)]_{LL} + ([\hat{\sigma}^{\mu})(\hat{\sigma}_\mu)]_{LR}^2 \]
\[ = (\alpha_1 / 2)(1 - v_{12})(1 - v_{13})(1 - v_{23}) \left[ 1 - \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ + (\alpha_2 / 2)(1 + v_{12})(1 + v_{13})(1 + v_{23}) \left[ 1 + \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ + (\alpha_3 / 2)(1 + v_{12})(1 + v_{13})(1 + v_{23}) \left[ 1 + \cos(\theta_0 - \theta_j - \theta_k) \right] \]
\[ - \cos(\theta_0 - \theta_k - \theta_j). \] (B-5)
After adding all colour combinations $\alpha_1, \alpha_2$ and $\alpha_3$ gives
\[ \alpha_1 = \left[ d_1 + d_2 + d_3 + d_4 \right]^2 \]
\[ + 2 \left[ d_1 + d_2 \right]^2 + 2 \left[ d_2 + d_4 \right]^2, \]
α₂ = |d₃ + d₆|² + 2|d₅|² + 2|d₆|² ,  
α₃ = Re{ (3d₁ + d₂ + d₃ + 3d₄)α₆* }  
+ (d₁ + 3d₂ + 3d₃ + d₄)α₆² ,  

(B-6)

The energy conservation gives  

\[
cos(θ_3 - θ_2) = \frac{(M_f - E_f - E_E)^2}{(m² + p²)} \]  
\[
- \frac{(m² + p²)}{2p_k p_k}, \]

\[
\cos(θ_3 - θ_2) = \frac{(M_f - E_f - E_E)^2}{(m² + p²)} \]  
\[
- \frac{(m² + p²)}{2p_k p_k}, \]

(B-7)

The angle between the particle velocities must be physical,  
-1 ≤ cos(θ₃ - θ₂) ≤ 1  
and so on. The partial decay rate, b spin averaged and summed over final spin states, has overall spherical symmetry. Apart from its overall orientation, a final state is specified by only two parameters, say  
\[ p₁ |p₁| \text{ and } p₂ |p₂| . \]

Then \( p_j \) is given by energy conservation  
\[
E_j = M_f - E_f - E_E = \sqrt{m^2 + p^2} . \]

Also  
\[
\cos(θ₃ - θ₂) = \frac{(p² - p² - p²)}{2p_1 p_1}, \text{ and so on.} \]

Momentum conservation gives  
\[ p_k \cos(θ₃ - θ₂) + p_j \cos(θ₃ - θ₂) = -p_1 , \]

(B-9)

and so on. Also \[ p_k \sin(θ₃ - θ₂) = ±p_j \sin(θ₃ - θ₂) . \]

(B-10)

and so on. The partial decay rate, b spin averaged and summed over final spin states, has overall spherical symmetry. Apart from its overall orientation, a final state is specified by only two parameters, say  
\[ p₁ |p₁| \text{ and } p₂ |p₂| . \]

The partial decay rate in the b rest frame is  
\[ d²Γ₁₂₃₄ = \frac{(G_f^2 / π^3) p₁ p_k E_f}{|p_1|^4} \{ α_i(p_i) p_k / E_i E_k \} \]

+ \[ α_2(p₁, p₇ / E_i E_j) + α₃(m_k m_j / E_i E_j) \],  

(B-11)

where \[ p₁ p_k = (M_b^2 + m² - m² - 2M_b E_f) / 2 \],  

(B-12)

After the change of variable to \( x \) and \( y \), the decay rate is given by  
\[ d²Γ₁₂₃₄ / dx dy = Γ_{ab} f_{ab} \],  

(B-13)

\[ f_{ab} = α_1 I₁ + α₂ I₂ + α₃ I₃ \],  

(B-14)

where \[ I₁ = 6xy f_ab(1 - h_{abc}) \],  

\[ I₂ = 6xy f_bc(1 + h_{bca}) \],  

\[ I₃ = 6xy f_ac h_{aca} h_{bca} \].  

(B-15)

Here  
\[ f_{ab} = 2 - \sqrt{x^2 + y^2} - \sqrt{y^2 + b²} \],  

(B-20)

\[ h_{abc} = \frac{(f_{ab})² - (c² + x² + y²)}{2\sqrt{x² + y²} + b²} \],  

(B-21)

\[ f_{bc} = 2 - \sqrt{x² + b²} - \sqrt{y² + c²} \],  

(B-22)

\[ h_{bca} = \frac{(f_{bc})² - (a² + x² + c²)}{2\sqrt{x² + y²} + c²} \],  

(B-23)

\[ f_{ac} = 2 - \sqrt{x² + a²} - \sqrt{y² + c²} \],  

(B-24)

\[ h_{cab} = \frac{(f_{ac})² - (b² + x² + y²)}{2\sqrt{x² + a²} + c²} \],  

(B-25)

\[ f_{ab} = 1 - (x² / (x² + c²))^{1/2} \],  

(B-26)

\[ h_{abc} = 1 - (y² / (y² + c²))^{1/2} \],  

(B-27)

where \( a, b \) and \( c \) are:  
\[ a = 2M_i / M_b, \quad b = 2M_i / M_b, \quad c = 2M_j / M_b \].  

(B-17)

\textbf{Appendix C}

\textbf{Effective Hamiltonian of magnetic dipole decay rate}

We calculate the decay rates of \( b \rightarrow q_i q_a \bar{q}_j \) according to effective Hamiltonian \( (Q_1, \ldots, Q_6) \), including magnetic dipole \( (Q_6) \) terms. The amplitude of Effective Hamiltonian for operators \( Q_1, Q_2, Q_3, Q_4 \) is given by  
\[ M_{1(1/2)}^{L-L} = A(d₁ + d₂ + d₃ + d₄)[\sin((θ₃ - θ_j - θ_i) / 2) \]

+ \[ \sin((θ_k + θ_j - θ_i) / 2)] \],  

(C-1)

and for operators \( Q₅, Q₆ \) is as well  
\[ M_{3(1/2)}^{L-L} = A(d₁ + d₂ + d₃ + d₄)[\cos((θ₃ - θ_j - θ_i) / 2) \]

- \[ \cos((θ_k + θ_j - θ_i) / 2)] \],  

(C-2)

where \( d₁, \ldots, d₆, d₈ \) and \( A₈ \) are defined by eq. (26) and (A-21) respectively and  
\[ A = \sqrt{(1 + v_i)(1 + v_k)(1 + v_j)(1 - v⁻²)} \],  

(A')  
\[ A' = \sqrt{(1 - v_i)(1 + v_k)(1 - v_j)(1 - v⁻²)} \],  

(C-3)

Also the amplitude of magnetic dipole according to \( (A-20) \) is given by  
\[ M_{dip} = \delta_{d₈}[\{k_L | \bar{σ}_μ | h_L \} | k_L | \bar{σ}_μ | h_L \} \]

+ \[ \{k_L | \bar{σ}_μ | h_L \} | k_L | \bar{σ}_μ | h_L \}],  

(C-4)
For various b spin project 1/2 and −1/2 the first term of (C-4) is given by
\[ M_{\text{spin ave}}^{\text{dip},L-R} = A_A d_A \left[ \sin(\theta_i - \theta_k^{(1)}) / 2 \right] + \sin((\theta_i + \theta_k^{(1)}) / 2) \]
\[ + \sin((\theta_i - \theta_k^{(2)}) / 2), \]
\[ M_{\text{spin ave}}^{\text{dip},L-R} = A_A d_A \left[ -\cos(\theta_i - \theta_k^{(1)}) / 2 \right] - \cos(\theta_i + \theta_k^{(1)}) / 2), \]
and the second term of (C-4) is given by
\[ M_{\text{tot}}^{\text{dip},L-R} = A_A d_A \left[ \cos(\theta_i - \theta_k^{(1)}) / 2 \right] - \cos(\theta_i + \theta_k^{(1)}) / 2), \]
\[ M_{\text{tot}}^{\text{dip},L-R} = A_A d_A \left[ \cos(\theta_i - \theta_k^{(2)}) / 2 \right] - \cos(\theta_i + \theta_k^{(2)}) / 2), \]
Here
\[ e_1 = A(d_1 + d_2 + d_3 + d_4) + A_k d_k, \]
\[ e_2 = A(d_1 + d_2 + d_3 + d_4) - A' A_k d_k, \]
\[ e_3 = A_k d_k + A'(d_k + A_k). \]
The spin average of b spin project of 1/2 and −1/2 is given by
\[ M_{\text{spin ave}}^{\text{dip},L-R} = \frac{1}{2} \left[ M_{\text{tot}}^{\text{dip},L-R} + M_{\text{tot}}^{\text{dip},L-R} \right] \]
\[ = \frac{1}{2} \left[ e_1^2 + e_2^2 + e_3^2 - 2e_1e_2 \cos(\theta_i - \theta_k^{(1)}) \right. \]
\[ + 2e_1e_3 \cos(\theta_i - \theta_k^{(1)}) - 2e_2e_3 \cos(\theta_i + \theta_k^{(1)}). \]
Adding all color factors, it gives
\[ e_1 = A(h_1 + h_2) + A' h_3, \]
\[ e_2 = Ah_1 + A' h_2, \]
\[ e_3 = Ah_2 + A' h_3, \]
where
\[ h_1 = \sqrt{d_1 + d_2 + d_3 + d_4^2 + 2|d_1 + d_4|^2 + 2|d_2 + d_3|^2}, \]
\[ h_2 = A_k d_k, \]
\[ h_3 = \sqrt{d_1^2 + d_2^2 + d_3^2 + 2|d_1|^2 + 2|d_2|^2 + 2|d_3|^2}, \]
The first term of (C-10) is given by
\[ e_1^2 + e_2^2 + e_3^2 = A^2(2h_1^2 + 2h_2^2 + 2h_3^2 + 2h_4^2) \]
\[ + A'(2h_1^2 + 2h_2^2 + 2h_3^2 + 2h_4^2), \]
\[ + 2A'A'(h_1^2 + h_2^2 + 2h_3^2 + 2h_4^2), \]
Adding eight terms of helicity states, so
\[ e_1^2 + e_2^2 + e_3^2 = 8(g_1 + g_2 + 2\sqrt{1 - v_1^2\sqrt{1 - v_j^2}} g_3), \]
The second term of (C-10) is given by
\[ 2e_1e_2 \cos(\theta_i - \theta_k^{(1)}) = 2A^2(h_1^2 + h_2^2) - A'^2(h_2^2 + h_3^2) \]
\[ + AA'(h_1 h_3 - h_2^2) \cos(\theta_i - \theta_k^{(1)}), \]
Adding eight terms of helicity states, so
\[ 2e_1e_2 \cos(\theta_i - \theta_k^{(1)}) = 2.8.v_j v_1(g_4 - g_5) \cos(\theta_i - \theta_k^{(1)}), \]
The third term of (C-10) is given by
\[ 2e_2e_3 \cos(\theta_i - \theta_k^{(1)}) = 2A^2(h_3^2 + h_4^2) - A'^2(h_2^2 + h_3^2) \]
\[ + AA'(h_1 h_3 - h_2^2) \cos(\theta_i - \theta_k^{(1)}), \]
Adding eight terms of helicity states, so
\[ 2e_2e_3 \cos(\theta_i - \theta_k^{(1)}) = 2.8.v_j v_1(g_6 + g_7) \cos(\theta_i - \theta_k^{(1)}), \]
The fourth term of (C-10) is given by
\[ 2e_1e_3 \cos(\theta_i - \theta_k^{(1)}) = 2A^2(h_1 h_2) - A'^2(h_2 h_3) \]
\[ + AA'(h_1 h_3 - h_2^2) \cos(\theta_i - \theta_k^{(1)}), \]
Adding eight terms of helicity states, so
\[ 2e_1e_3 \cos(\theta_i - \theta_k^{(1)}) = 2.8.v_j v_1(g_8 - g_9) \cos(\theta_i - \theta_k^{(1)}), \]
Here
\[ g_1 = 2h_1^2 + 2h_2^2 + 2h_3^2, \]
\[ g_2 = 2h_1^2 + 2h_2^2 + 2h_3^2, \]
\[ g_3 = h_2^2 + h_3^2 + 3h_4^2, \]
\[ g_4 = h_1^2 + h_2^2, \]
\[ g_5 = h_2^2 + h_3^2 + h_4^2, \]
\[ g_6 = h_1^2 + h_2^2 + h_3^2, \]
\[ g_7 = h_2^2 + h_3^2 + h_4^2, \]
\[ g_8 = h_1^2 + h_2^2 + h_3^2, \]
\[ g_9 = h_1^2 + h_2^2 + h_3^2, \]
\[ g_j = h_1^2 + h_2^2 + h_3^2, \]
The total amplitude of (C-10) is given by
\[ M_{\text{tot}}^{\text{dip},L-R} = \left[ g_1 + g_2 - 2\sqrt{1 - v_1^2\sqrt{1 - v_j^2}} g_3 \right. \]
\[ - 2v_j v_1(g_4 - g_5) \cos(\theta_i - \theta_k^{(1)}) \]
\[ + 2v_j v_1(g_6 + g_7) \cos(\theta_i - \theta_k^{(1)}), \]
\[ - 2v_j v_1(g_8 - g_9) \cos(\theta_i - \theta_k^{(1)}). \]
Also one can obtain the amplitude of tree-level and Effective Hamiltonian \((Q_1,...,Q_6)\). The amplitude of tree-level \((d_2 = d_3 = d_4 = d_5 = d_6 = d_8 = 0)\) is given by

\[
|M_{\text{tree}}|^2 = \frac{1}{4} \left[ 2h_i^2 - 2h_i^2 v_i v_k \cos(\theta_k - \theta_i) + 0 + 0 \right]
\]

\[
= 3d_i^2 \frac{1}{2} \left[ (1 - v_i v_k \cos(\theta_k - \theta_i)) \right] \quad \text{(C-24)}
\]

and the amplitude of effective Hamiltonian \((d_8 = 0)\) is given by

\[
|M_{\text{EH}}|^2 = \left( \frac{h_i^2}{2} \right) \left[ (1 - v_i v_k \cos(\theta_k - \theta_i)) \right]
\]

\[
+ \left( \frac{h_j^2}{2} \right) \left[ (1 + v_j v_k \cos(\theta_j - \theta_k)) \right]
\]

\[
- \left( \frac{1 - v_i^2}{\sqrt{1 - v_i^2}} \right) \left( \frac{1 - v_j^2}{\sqrt{1 - v_j^2}} / 4 \right) (2h_i h_j) \quad \text{(C-25)}
\]

After integration in the phase space and changing the variables \(x\) and \(y\),

\[
\frac{d^2 \Gamma}{dxdy} = \frac{G_F^2 M_Z^2}{192\pi^3} \frac{1}{2} \left( I_1 + I_2 + I_3 \right),
\]

where

\[
I_1 = 6xy f_{ab} \left[ g_2 - 2(g_4 - g_5) h_{abc} \right],
\]

\[
I_2 = 6xy f_{bc} \left[ g_2 + 2(g_6 + g_7) h_{bca} \right],
\]

\[
I_3 = 6xy f_{ac} \left[ -2g_3 h_{ax} h_{yc} - 2(g_8 - g_9) h_{ach} \right],
\]

and \(f_{ab}, f_{bc}, f_{ac}, h_{abc}, h_{bca}, h_{ach}, h_{ax} \) defined by (B-16).

References