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Perturbative QCD study on the photonic penguin contributions to the decay $B \to K^*\gamma$

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Abstract. Including corrections of order $O(m_{K^*}/m_B)$, we present an analysis of photonic penguin contributions to the decay $B \to K^*\gamma$ in the perturbative QCD framework. Employing several models of the meson wave functions, we demonstrate that the corrections of $O(m_{K^*}/m_B)$ are enhanced and will provide substantial contributions to the decay because of the B meson wave function being sharply peaked (bound state effect). The numerical predictions for the corrections are about 30% $\sim$ 60% which depend on the non-perturbative inputs such as the meson wave functions and the b-quark mass.

1 Introduction

The rare decay $B \to K^*\gamma$ has attracted great attentions especially after the CLEO Collaboration first identified this decay and gave its branching ratio [1]. The decay $B \to K^*\gamma$ is dominated by the flavor-changing quark-level process $b \to s\gamma$ which can occur not only through penguin diagram at one-loop level in the standard model (SM) but also through virtual particle in the supersymmetry and other extensions of the standard model [2,3]. Thus accurate experimental measurements and theoretical calculations of this decay can provide a precision test of the standard model as well as a test of new physics at present experimentally accessible energy scale. It has been pointed out [4] that perturbative QCD (PQCD) may be applicable to the exclusive nonleptonic decays of B meson since there is a hard-gluon exchange between the heavy and light quarks in these decays. Recently calculations also show that PQCD may give a good description of the two body hadronic decays of B meson [5].

In the standard model (SM), the mainly contribution to the decay $B \to K^*\gamma$ comes from the photonic penguin diagrams which are shown in Fig. 1. Compared to Fig. 1a, the contribution from Fig. 1b is of order m_{K^*}/m_B, and thereby it is not included in [6]. In this paper we shall re-analyse decay $B \to K^*\gamma$ in the SM by including $O(m_{K^*}/m_B)$ corrections in the amplitude. Including bound state effect and employing several models of distribution amplitudes of B and K^* mesons, we find that these corrections are enhanced by the bound state effect and become more important. This paper is organized as follows: In Sect. 2, we calculate the photonic penguin diagram contributions to the order m_{K^*}/m_B in the amplitude after describing the effective Hamiltonian. In Sect. 3, we present numerical results by employing several models of meson distribution amplitudes. As usual, the last section is reserved for summary.

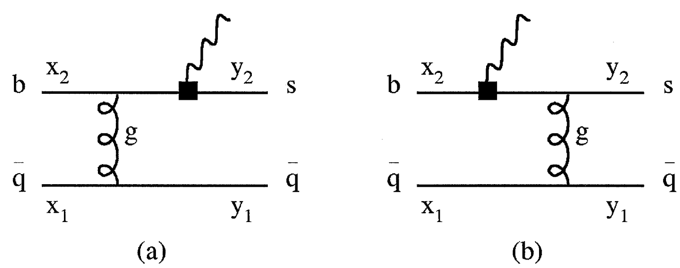

Fig. 1. The photonic penguin diagram. The *square blob* represents the effective vertex

2 Contribution coming from photonic penguin diagram

The effective Hamiltonian (the square blob part in Fig. 1) which describes the photonic penguin diagram, can be expressed as [7–9]

$$H_{eff} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* C_7(\mu) O_7(\mu), \tag{1}$$

where

$$O_7(\mu) = \frac{e}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu} F_{\mu\nu} \frac{1}{2}(1+\gamma_5) b. \tag{2}$$

In the above expressions, $C_7(\mu)$ is the Wilson coefficient which contains the effects of QCD corrections,

$$C_7(\mu) = \eta^{-16/3\beta_0} \left[C_7(m_W) - \frac{58}{135} \left(\eta^{10/3\beta_0} - 1 \right) \right.$$

$$-\frac{29}{189}\left(\eta^{28/3\beta_0}-1\right)\Bigg], \tag{3}$$

where $\eta=\alpha_s(\mu)/\alpha_s(m_W)$, $\beta_0=11-(2/3)n_f$ and $C_7(m_W) = -0.19$ is given in the W-mass scale.

The wave function of the B meson can be written in the form [4]

$$\psi_B=\frac{1}{2}\frac{I_c}{\sqrt{3}}\phi_B(x)\gamma_5(\not p_B-m_B), \tag{4}$$

where I_c is the identity in the color space. For the K^* meson, the wave function can be expressed as

$$\psi_{K^*}=\frac{1}{2}\frac{I_c}{\sqrt{3}}\phi_{K^*}(x)\not\xi^*(\not p_{K^*}+m_{K^*}), \tag{5}$$

where ξ^* is the polarization vector of the K^* meson. ϕ_B and ϕ_{K^*} are the distribution amplitudes of the B and K^* mesons respectively.

We express the contribution to the amplitude in the gauge invariant form[1]

$$M_i=t_i\times\frac{1}{2p_B\cdot q}\left[p_B\cdot q\epsilon^*\cdot\xi^*-p_B\right.$$
$$\left.\cdot\epsilon^* q\cdot\xi^*+i\epsilon_{\mu\nu\alpha\beta}p_B^\mu q^\nu\epsilon^{*\alpha}\xi^{*\beta}\right]. \tag{6}$$

The contributions from Figs. 1a and 1b can be written as

$$\begin{aligned}
t_1 &= Gm_b\int[dx][dy]\phi_B(x)\phi_{K^*}(y)\frac{1}{l_b^2-m_b^2}\frac{1}{k_g^2}\\
&\quad\times Tr\left\{\frac{\gamma_5(\not p_B-m_B)}{\sqrt{2}}\gamma^\alpha\frac{\not\xi^*(\not p_{K^*}+m_{K^*})}{\sqrt{2}}\right.\\
&\quad\left.\sigma^{\mu\nu}F_{\mu\nu}\frac{1}{2}(1+\gamma_5)(\not l_b+m_b)\gamma_\alpha\right\}\\
&= 4Gm_b\int_0^1[dx]\frac{1}{x_1}\phi_B(x)\\
&\quad\times\int_0^1[dy]\frac{(1-y_1)m_B^2-2m_bm_B}{y_1\left[m_b^2-(1-y_1)m_B^2\right]}\phi_{K^*}(y)\\
&\quad+4Gm_b\int_0^1[dx]\frac{1}{x_1}\phi_B(x)\\
&\quad\times\int_0^1[dy]\frac{\left[m_b-2(1-y_1)m_B\right]m_{K^*}}{y_1\left[m_b^2-(1-y_1)m_B^2\right]}\phi_{K^*}(y)\\
&\equiv 4Gm_bI_{1B}I_{1K^*}^{LO}+4Gm_bI_{1B}I_{1K^*}^{NLO}\\
&\equiv t_1^{LO}+t_1^{NLO}
\end{aligned} \tag{7}$$

and

$$\begin{aligned}
t_2^{NLO} &= Gm_b\int[dx][dy]\phi_B(x)\phi_{K^*}(y)\frac{1}{l_b^2-m_b^2}\frac{1}{k_g^2}\\
&\quad\times Tr\left\{\frac{\gamma_5(\not p_B-m_B)}{\sqrt{2}}\gamma^\alpha\frac{\not\xi^*(\not p_{K^*}+m_{K^*})}{\sqrt{2}}(\not l_b+m_b)\right.\\
&\quad\left.\times\sigma^{\mu\nu}F_{\mu\nu}\frac{1}{2}(1+\gamma_5)\gamma_\alpha\right\}\\
&= -4Gm_b\int_0^1[dx]\frac{1-x_1}{x_1^2}\phi_B(x)\int_0^1[dy]\frac{m_{K^*}}{y_1m_B}\phi_{K^*}(y)\\
&\equiv -4Gm_bI_{2B}I_{2K^*}^{NLO},
\end{aligned} \tag{8}$$

[1] It is worthwhile to note that the expression for the amplitude presented here, (6), is gauge invariant, while the one given in [6] is not because of the second term in the bracket of (6) being missed [10]

In the above expressions, $[dx]=dx_1dx_2\delta(1-x_1-x_2)$, $[dy]=dy_1dy_2\delta(1-y_1-y_2)$, q and ϵ are the momentum and polarization of the photon respectively, and

$$G=\frac{G_F}{\sqrt{2}\pi}V_{tb}V_{ts}^*C_FC_7(\mu)e\alpha_s(\mu). \tag{9}$$

x_1 and y_1 in (7) and (8) are the momentum fractions carried by the light quarks in the B and K^* mesons respectively. The distribution amplitude of B meson, $\phi_B(x)$, should be sharply peaked at some small value of x_1 since m_b is much larger than the light quark mass [4,6]. Thus we keep only the leading contributions of x_1 in the quark and gluon propagators, which are x_1 terms in Fig. 1a and x_1^2 terms in Fig. 1b. The fermion propagators in Figs. 1a and 1b contribute different factors to t_1 and t_2: The one in Fig. 1a involving only K^* meson variable in the form of $1/[y_1m_b^2-(m_B^2-m_b^2)]$ is attributed to the integrals $I_{1K^*}^{LO}$ and $I_{1K^*}^{NLO}$; The one in Fig. 1b involving only B meson variable in the form of $1/(x_1m_B^2)$ is attributed to the integral I_{2B}. The gluon propagators in Figs. 1a and 1b involving both B and K^* meson variables in the form of $1/(x_1y_1m_B^2)$ can be factored to the integrals I_{iB} and I_{iK}. In this way, t_i is factorized to two independent integrals I_{iB} and I_{iK^*}.

In (7) and (8), t_1^{LO} provides leading contribution while t_1^{NLO} and t_2^{NLO} are corrections of $O(m_{K^*}/m_B)$. It is interested to notice that the suppression factor m_{K^*}/m_B in t_2^{NLO} can be compensated by the bound state effect as it is going to be demonstrated in the following. Compared to I_{1B}, the fermion propagator in Fig. 1b provides an additional factor $1/x_1$ to I_{2B}. Because the distribution amplitude of B meson, ϕ_B, is sharply peaked at $x_1\approx 0.05\sim 0.1$ [4], I_{2B} is much larger than I_{1B}. For example, employing a simple model for ϕ_B, $\phi_B\sim\delta(x_1-\epsilon_B)$ with

$$\epsilon_B=\frac{m_B-m_b}{m_B}, \tag{10}$$

the ratio is (see Table 1)

$$\frac{I_{2B}}{I_{1B}}=\frac{1-\epsilon_B}{\epsilon_B}=\frac{m_b}{m_B-m_b}\approx 10\sim 18. \tag{11}$$

This factor will cancel approximately the suppression factor m_{K^*}/m_B being about 1/17 in $I_{2K^*}^{NLO}$, which make the contribution coming from Fig. 1b become important. There is no similar enhancement factor in t_1^{NLO}, so it is order m_{K^*}/m_B and may be neglected as compared to t_1^{LO}.

It has been pointed out [6] that the contribution coming from Fig. 1a, t_1^{LO}, contains a large imaginary part because of the pole of the heavy quark propagator. This imaginary part does not correspond to the long-distance physics. It should be noticed that the ratio of the imaginary part to the real part depends on the b-quark mass

m_b (namely ϵ_B) and $B(K^*)$ distribution amplitudes (see Table 2), which are about $3.5 \sim 0.8$. Thus the contribution form Fig. 1b should be taken into account although it provides only a real contribution.

The decay width and branching ratio can be obtained readily,

$$\Gamma = \frac{1}{16\pi m_B}\left|\sum_{polarization}(M_1+M_2)\right|^2, \qquad (12)$$

$$Br(B \to K^*\gamma) = \frac{\Gamma}{\Gamma_{total}}. \qquad (13)$$

3 Numerical calculation and model analysis

For the numerical results, we take the following parameters as inputs:

$$\begin{aligned} \Lambda_{QCD} &= 200 \text{ MeV}, & \mu &= 1 \text{ GeV}, \\ m_W &= 81 \text{ GeV}, & m_t &= 2m_W, \\ V_{tb} &= 0.999, & V_{ts} &= -0.045, \\ f_B &= 132 \text{ MeV[11]}, & f_{K^*} &= 151 \text{ MeV[12]}, \\ \tau_B &= 1.46\times 10^{-12} \text{ second}. \end{aligned} \qquad (14)$$

The numerical results should depend on the expressions of distribution amplitudes $\phi_B(x)$ and $\phi_{K^*}(y)$ which are determined by the non-perturbative physics. For the ϕ_B we adopt the following models: i) According to Brodsky-Huang-Lepage prescription [13] the B meson wave function can be given in the form [14],

$$\begin{aligned} &\psi_B(x,k_\perp) \qquad (15) \\ &= A\exp\left[-b^2\left(\frac{m_b^2+k_\perp^2}{x_2}+\frac{m_q^2+k_\perp^2}{x_1}\right)\right], \end{aligned}$$

in which the parameters A and b are determined by two constraints:

$$\int_0^1 [dx]\frac{d^2\mathbf{k}_\perp}{16\pi^3}\psi_B(x,k_\perp) = \frac{f_B}{2\sqrt{3}}, \qquad (16)$$

and

$$P_B = \int_0^1 [dx]\frac{d^2\mathbf{k}_\perp}{16\pi^3}\left|\psi_B(x,k_\perp)\right|^2 \approx 1. \qquad (17)$$

P_B is the probability of finding the $|q\bar{q}\rangle$ Fock state in the B meson. The second constraint $P_B \approx 1$ is reasonable since with the increase of the constitute quark mass the valence Fock state occupies the most fraction in the hadron, and in the nonrelativistic limit the probability of finding the valence Fock state is going to approach unity. Then we can obtain the distribution amplitude of B meson

$$\begin{aligned}\phi_B^{BHL}(x) &= \frac{A}{16\pi^2 b^2}x_1x_2 \\ &\times\exp\left[-b^2\left(\frac{m_b^2}{x_2}+\frac{m_q^2}{x_1}\right)\right]. \end{aligned} \qquad (18)$$

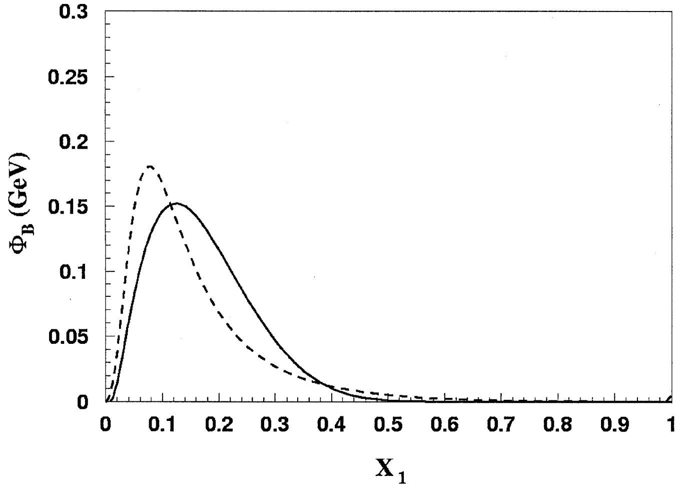

Fig. 2. The distribution amplitudes of B meson employed in our calculation: ϕ_B^{BHL} (the *solid curve*) with $m_b = 4.9$ GeV and $m_q = 0.35$ GeV; ϕ_B^{SHB} (the *dashed curve*) with $\epsilon_B = 0.072$; $\phi_B^\delta \sim \delta(x_1 - 0.072)$ is not plotted in this figure

ii) Szczepaniak, Henley and Brodsky suggested another model for $\phi_B(x)$ [4],

$$\phi_B^{SHB}(x) = \frac{A}{\left(\epsilon_B^2/x_1 + 1/x_2 - 1\right)^2}, \qquad (19)$$

where A and ϵ_B are given by (16) and (10) respectively. iii) The simplest model for ϕ_B is the δ-function approximation which has been adopted in [5,6]

$$\phi_B^\delta(x) = \frac{f_B}{2\sqrt{3}}\delta(x_1-\epsilon_B), \qquad (20)$$

where ϵ_B is related to the longitudinal momentum fraction of the light quark (see (10)).

We adopt the following two models for ϕ_{K^*}: i) it has been pointed out [14–16] that K^* meson wave function is close to its asymptotic behavior, so we adopt the expression in [14],

$$\begin{aligned}\phi_{K^*}(x) &= \frac{A}{16\pi^2 b^2}y_1y_2 \\ &\times\exp\left[-b^2\left(\frac{m_s^2}{y_2}+\frac{m_q^2}{y_1}\right)\right], \end{aligned} \qquad (21)$$

where $A = 41.4$ GeV^{-1}, $b = 0.74$ GeV^{-1}, $m_s = 0.55$ GeV and $m_q = 0.35$ GeV. The quark masses appearing in the meson wave functions (distribution amplitudes) should be the constituent quark masses since the wave function is determined mainly by the soft-physics, while the quark masses appearing in the hard amplitudes should be the current quark masses which can be ignored reasonably for the light quarks. ii) The asymptotic expression for ϕ_{K^*},

$$\phi_{K^*}(y) = \sqrt{3}f_{K^*}y_1y_2. \qquad (22)$$

The numerical results are given in Tables 2 and 3. ϕ_B^{BHL}, ϕ_B^{SHB} and ϕ_B^δ have different behavior in the x-space (see Fig. 2). ϕ_B^{BHL} is not so sharply peaked as ϕ_B^{SHB}

Table 1. ϕ_B-dependence of t_i

	ϕ_B^{BHL}			ϕ_B^{SHB}			ϕ_B^{δ}		
m_b(GeV)	4.8	4.9	5.0	4.8	4.9	5.0	4.8	4.9	5.0
I_{1B}	0.29	0.30	0.31	0.38	0.46	0.59	0.42	0.53	0.72
I_{2B}	3.50	3.63	3.77	7.16	10.7	18.4	4.20	6.83	12.8

Table 2. Decay amplitudes in unit of 10^{-8}GeV

		$\phi_{k^*}^{GH}$			$\phi_{k^*}^{as}$		
m_b(GeV)		4.8	4.9	5.0	4.8	4.9	5.0
ϕ_B^{BHL}	t_1^{LO}	-1.40-2.29I	-1.87-2.29I	-2.44-2.12I	-0.68-2.32I	-0.97-2.44I	-1.35-2.66I
	t_1^{NLO}	0.01-0.29I	-0.06-0.31I	-0.14-0.30I	0.12-0.28I	0.08-0.32I	0.03-0.38I
	t_2^{NLO}	-0.79	-0.84	-0.89	-0.86	-0.91	-0.97
ϕ_B^{SHB}	t_1^{LO}	-1.80-2.94I	-2.83-3.45I	-4.63-4.03I	-0.88-2.88I	-1.47-3.69I	-2.58-5.05I
	t_1^{NLO}	0.01-0.37I	-0.08-0.47I	-0.27-0.58I	0.15-0.36I	0.13-0.50I	0.06-0.72I
	t_2^{NLO}	-1.63	2.47	-4.33	-1.76	-2.69	-8.13
ϕ_B^{δ}	t_1^{LO}	-1.96-3.24I	-3.24-3.96I	-5.63-4.87I	-0.96-3.15I	-1.68-4.24I	-3.13-6.15I
	t_1^{NLO}	0.01-0.41I	-0.10-0.53I	-0.33-0.70I	0.16-0.40I	0.15-0.56I	0.80-0.87I
	t_2^{NLO}	-0.95	-1.57	-3.02	-1.03	-1.72	-3.29

Table 3. Branching ratio $Br(B \to K^*\gamma)$ in unit of $\times 10^{-5}$

		$\phi_{k^*}^{GH}$			$\phi_{k^*}^{as}$		
m_b(GeV)		4.8	4.9	5.0	4.8	4.9	5.0
ϕ_B^{BHL}	Br^{LO}	0.60	0.73	0.87	0.46	0.58	0.74
	Br^{Full}	0.95	1.20	1.50	0.70	0.91	1.21
	$\frac{Br^{Full}-Br^{LO}}{Br^{Full}}$	37%	39%	42%	34%	36%	39%
ϕ_B^{SHB}	Br^{LO}	0.99	1.66	3.16	0.76	1.32	2.69
	Br^{Full}	1.89	3.70	8.90	1.40	2.83	7.16
	$\frac{Br^{Full}-Br^{LO}}{Br^{Full}}$	48%	53%	65%	46%	53%	62%
ϕ_B^{δ}	Br^{LO}	1.19	2.19	4.65	0.90	1.74	3.96
	Br^{Full}	1.80	3.71	9.35	1.33	2.82	7.47
	$\frac{Br^{Full}-Br^{LO}}{Br^{Full}}$	34%	41%	50%	32%	38%	50%

and ϕ_B^{δ}, and the position of the maximum of ϕ_B^{BHL} is farther away the end-point $x_1 = 0$ than that of the other two models *i.e.* ϕ_B^{BHL} does not emphasize the small-x_1 region so strongly as ϕ_B^{SHB} and ϕ_B^{δ} do. Thus the value of I_{1B} (I_{2B}) calculated with ϕ_B^{BHL} is the smallest one among the three models (see Table 1). Because of t_1 and t_2 depending on ϕ_B only through the integrals I_{1B} and I_{2B} respectively (see (7) and (8)), the decay amplitude and branching ratio calculated with ϕ_B^{BHL} will be also the smallest one (see Table 3).

It can be found that t_1^{NLO} is about 1/10 of t_1^{LO} because of the suppression factor m_{K^*}/m_B, while t_2^{NLO} is the same order as the real part of t_1^{LO} since the bound state effect compensates approximately the suppression factor m_{K^*}/m_B (see Table 2). The corrections to the decay branching ratio are about 30% $\sim$ 60% which varies with the distribution amplitudes of B and K^* mesons and the b-quark mass. The corrections calculated with ϕ_B^{SHB} is more important than that with the other two models, and the corrections calculated with $\phi_{K^*}^{GH}$ and $\phi_{K^*}^{as}$ are very similar since they have similar behavior. It can been found also that the corrections become more important with m_b increasing. We would like to point out again that it is because the distribution amplitude of B meson should be sharply peaked at some small value of $x_1 = \epsilon_B$ (the bound state effect) that the corrections of $O(m_{K^*}/m_B)$ coming from Fig. 1b become more important.

As comparing with the experimental data, we find that the results calculated with ϕ_B^{SHB} and ϕ_B^{δ}, and with m_b being about 4.9 are comparable to the experiment data $Br(B \to K^*\gamma) = 4.5 \pm 1.5 \pm 0.9 \times 10^{-5}$ [1].

4 Summary

The decay $B \to K^*\gamma$ is a very attractive process since it provides an experimentally accessible way for a subtle test of the standard model and a test of new physics. Both more accurate theoretical calculations and experimental measurements about this decay mode are worthwhile and necessary. By including the corrections of order m_{K^*}/m_B in the photonic penguin diagrams, we have analysed the decay $B \to K^*\gamma$ in the framework of perturbative QCD. Employing several models of the meson wave functions, we find that the $O(m_{K^*}/m_B)$ corrections coming from Fig. 1b provides substantial corrections to the branching ratio since the bound state effect provides an enhancement factor $m_b/(m_B - m_b)$ which cancels approximately the suppression factor m_{K^*}/m_B. The corrections are about about $30\% \sim 60\%$ which depend on the non-perturbative inputs such as the meson wave functions and the b-quark mass.

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