RADIATIVE $B^* \to B\gamma$ and $D^* \to D\gamma$ DECAYS IN LIGHT CONE QCD SUM RULES.

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Abstract

The radiative decays $B^*(D^*) \to B(D)\gamma$ are investigated in the framework of light cone QCD sum rules. The transition amplitude and decay rates are estimated.It is shown that our results on branching ratios of D meson decays are in good agreement with the existing experimental data.

1 Introduction

One of the main goals of the future B meson and charm- τ factories is a deeper and more comprehensive investigation of the B- and D-meson physics.

The radiative decays constitute an important for a comprehensive study the properties of the new meson states containing heavy quark. However, for interpretation of the experimental results we immediately deal with large distance effects. It is well known that QCD sum rules method [1] take into account such large distance effects and a powerfull tool for investigating the properties of hadrons. Nowadays, in current literature, an alternative to "classical QCD sum rules method", the QCD sum rules based on light cone expansion is widely exploited. Main features of this version is that it is based on the approximate conformal non-perturbative invariance of QCD, and instead of many process-dependent non-perturbative parameters in classical "QCD sum rules", it involves a new universal non-perturbative parameter, namely the wave function [3]. This sum rules previously were succesful applied for calculation the decay amplitude $\Sigma \to p\gamma$ [4], the nucleon magnetic moment, $g_{\pi NN}$ and $g_{\rho\omega\pi}$ couplings [5], form factors of semileptonic and radiative decays [6-9], the $\pi A\gamma^*$ form factor [10], $B \to \rho\gamma$ and $D \to \rho\gamma$ decays [11,12], $B^*B\pi$ and $D^*D\pi$ coupling constants [13] etc. In this work we study the radiative $B^*(D^*) \to B(D)\gamma$ decays in the framework of the light cone QCD sum rules. Note that these decays were investigated Ref. [14,15], in the framework of classical QCD sum rules method.

The paper is organized as follows.In section 2, we derive the sum rules which describes $B^*(D^*) \to B(D)\gamma$ in the framework of the light-cone sum rules. In the last section we present the numerical analysis.

2 The Radiative $B^* \to B\gamma$ decay

According to the general strategy of QCD sum rules, we want to obtain the transition amplitude for $B^* \to B\gamma$ decay, by equating the representation of a suitable correlator function in hadronic and quark-gluon language. For this aim we consider the following correlator

$$\Pi_\mu(p,q) \;=\; i\int d^4x e^{ipx} < 0|T[\bar{q}(x)\gamma_\mu b(x), \bar{b}(0)i\gamma_5 q(0)]|0>_F \tag{1}$$

in the external electromagnetic field

$$F_{\alpha\beta}(x) = i(\epsilon_\beta q_\alpha - \epsilon_\alpha q_\beta)e^{iqx} \tag{2}$$

Here q is the momentum and ϵ_μ is the polarization vector of the electromagnetic field. The Lorentz decomposition of the correlator is

$$\Pi_\mu = i\epsilon_{\mu\nu\alpha\beta}p_\nu\epsilon_\alpha q_\beta \Pi \tag{3}$$

Our main problem is to calculate Π in Eq. (3). This problem can be solved in the Euclidean space where both, p^2 and $p'^2 = (p+q)^2$ are negative and large. In this deep Euclidean region, photon interact with the heavy quark perturbatively. The various contributions to the correlator function Eq.(1) are depicted in Fiq. (1), where diagrams (a) and (b) represent the perturbative contributions, (c) is the quark condensate, (d) is the 5-dimensional operator, (e) is the photon interaction with soft quark line (i.e. large distance effects), and (f) is the three particle high twist contributions. A part of calculations of these diagrams was performed in [12,14,15].

First, let us calculate the perturbative contributions, namely diagram (b). After standard calculation of the bare loop we have

$$\Pi_1 \;=\; \frac{Q_q}{4\pi^2}N_c\int_0^1 xdx\int_0^1 dy\frac{m_b\bar{x}+m_a x}{m_a^2 x + m_b^2\bar{x} - p^2 x\bar{x}y - p'^2 x\bar{x}\bar{y}} \tag{4}$$

where $N_c = 3$ is the color factor, $\bar{x} = 1 - x$,$\bar{y} = 1 - y$, $p' = p + q$, Q_q and m_a are the charge and the mass of the light quarks. Note that the contribution of the diagram (a) can be obtained by making the following replacements in Eq. (4) : $m_b \leftrightarrow m_a, e_q \leftrightarrow e_Q$. The next step is to use the exponetial representation for the denominator

$$\frac{1}{C^n} = \frac{1}{(n-1)!}\int_0^\infty d\alpha \alpha^{n-1} e^{-\alpha C}$$

Then

$$\Pi_1 = \frac{Q_q N_c}{4\pi^2}\int_0^1 x dx \int_0^1 dy [m_b \bar{x} + m_a x] \int_0^\infty d\alpha e^{(m_a^2 x + m_b^2 \bar{x} - p^2 x\bar{x}y - p'^2 x\bar{x}\bar{y})} \tag{5}$$

Application of the double Borel operator $\hat{B}(M_1^2)\hat{B}(M_2^2)$ on Π_1 gives

$$\tilde{\Pi}_1 = \frac{Q_q N_c}{4\pi^2}\frac{\sigma_1\sigma_2}{\sigma_1+\sigma_2}\int_0^1 dx \frac{1}{\bar{x}}[m_b\bar{x} + m_a x]\, exp\{-\frac{m_a^2 x + m_b^2 \bar{x}}{x\bar{x}}(\sigma_1+\sigma_2)\} \tag{6}$$

where $\sigma_1 = \frac{1}{M_1^2}$ and $\sigma_2 = \frac{1}{M_2^2}$. In deriving Eq. (6) we use the definition

$$\hat{B}(M^2)e^{-\alpha^2} = \delta(1 - \alpha M^2) \tag{7}$$

Now consider the combination

$$\frac{1}{st}\hat{B}(\frac{1}{s},\sigma_1)\hat{B}(\frac{1}{s},\sigma_2)\frac{\tilde{\Pi}_1}{\sigma_1\sigma_2} \tag{8}$$

which just gives the spectral density [16]. Using Eq. (6) and Eq. (8), for the spectral density, we get

$$\begin{aligned}\rho_1(s,t) &= \frac{Q_q N_c}{4\pi^2}\int_{x_0}^{x_1} dx \delta(s-t)\theta(s-(m_b+m_a)^2)\theta(t-(m_b+m_a)^2) \\ &\cdot \frac{(m_b\bar{x} + m_a x)}{\bar{x}}\end{aligned} \tag{9}$$

where the integration region is determined by the inequality

$$sx\bar{x} - (m_b^2\bar{x} + m_a^2 x) \geq 0 \tag{10}$$

Using Eq. (9) for the spectral density, we get

$$\begin{aligned}
\rho_1^a(s,t) &= \frac{Q_q N_c}{4\pi^2}\delta(s-t)\theta(s-(m_b+m_a)^2)\theta(t-(m_b+m_a)^2) \\
\{ &- (m_b-m_a)\lambda(1,\kappa,l) + m_b ln\frac{1+\kappa-l+\lambda(1,\kappa,l)}{1+\kappa-l-\lambda(1,\kappa,l)}\} \qquad (11) \\
\rho_2(s,t) &= \rho_1(a\leftrightarrow b, m_a\leftrightarrow m_b, Q_a\leftrightarrow Q_b) \qquad (12)
\end{aligned}$$

where $\kappa=\frac{m_a^2}{s}, l=\frac{m_b^2}{s}$ and

$$\lambda(1,\kappa,l)=\sqrt{1+\kappa^2+l^2-2\kappa-2l-2\kappa l} \qquad (13)$$

Finally for the perturbative part of the correlator we have

$$\Pi^{Per}=\frac{N_c}{4\pi^2}\int ds\frac{1}{(s-p^2)(s-p'^2)}[(Q_a-Q_b)(1-\frac{m_b^2}{s})+Q_b ln\frac{s}{m_b^2}] \qquad (14)$$

Here we have neglected the mass of the light-quark. Applying Eq. (7), the Borel transformation, we get

$$\Pi^{Per}=\frac{N_c}{M_1^2M_2^2 4\pi^2}\int ds e^{-s(\frac{1}{M_2^2}+\frac{1}{M_2^2})}[(Q_a-Q_b)(1-\frac{m_b^2}{s})+Q_b ln\frac{s}{m_b^2}] \qquad (15)$$

After simple calculation, for the double Borel transformed quark condensate contribution, we have:

$$\Pi^{\bar{q}q}=Q_b<\bar{q}q>\frac{1}{M_1^2M_2^2}e^{-\frac{m_b^2}{M_1^2+M_2^2}} \qquad (16)$$

and the 5-dimensional operator contribution is

$$\begin{aligned}
\Pi^{\bar{q}q} &= Q_b<\bar{q}q>\frac{1}{M_1^2M_2^2}e^{-\frac{m_b^2}{M_1^2+M_2^2}} \\
&\cdot \{-\frac{m_0^2m_b^2}{4}(\frac{1}{M_1^2}+\frac{1}{M_2^2})^2+\frac{1}{3}\frac{m_0^2}{M_2^2}\} \qquad (17)
\end{aligned}$$

For the calculation of the diagram corresponding to the propogation of the soft quark in the external electromagnetic field, we use the light cone

expansion for non-local operators. After contracting the b-quark line in Eq(1) we get

$$\Pi_\mu = i\int d^4x \frac{d^4k}{(2\pi)^4 i}\frac{e^{i(p-k)x}}{m_b^2-k^2} < 0|\bar{q}(x)\gamma_\mu(m_b+\not{k})\gamma_5 q(x)|0>_F \tag{18}$$

Using the identity $\gamma_\mu\gamma_\alpha\gamma_5 = g_{\mu\alpha}\gamma_5 + i\sigma_{\rho\beta}\epsilon_{\mu\alpha\rho\beta}$ Eq. (18) can be written as

$$\Pi_\mu = -\epsilon_{\mu\alpha\rho\beta}\int d^4x \frac{d^4k}{(2\pi)^4 i}\frac{e^{i(p-k)x}k_\alpha}{m_b^2-k^2} < 0|\bar{q}(x)\sigma_{\rho\beta}q|0>_F \tag{19}$$

The leading twist-two contribution to this matrix element in the presence of the external electromagnetic field is defined as [4]:

$$< \bar{q}(x)\sigma_{\rho\beta}q >_F = Q_q < \bar{q}q > \int_0^1 du\phi(u)F_{\alpha\beta}(ux) \tag{20}$$

Here the function $\phi(u)$ is the photon wave function. The asymptotic form of this wave function is well known [4,17,18] to be,

$$\phi(u) = 6\xi u(1-u) \tag{21}$$

where ξ is the magnetic susceptibility.

The most general decomposition of the relevant matrix element, to the twist-4 accuracy, involves two new invariant functions (see for example [11,12]):

$$\begin{aligned} < \bar{q}(x)\sigma_{\rho\beta}q >_F &= Q_q < \bar{q}q > \{\int_0^1 dux^2\phi_1(u)F_{\rho\beta}(ux) \\ &+ \int_0^1 du\phi_2(u)[x_\beta x_\eta F_{\rho\eta}(ux) \\ &- x_\rho x_\eta F_{\beta\eta}(ux) - x^2 F_{\rho\beta}(ux)]\} \end{aligned} \tag{22}$$

In [11] it was shown that

$$\begin{aligned} \phi_1(u) &= -\frac{1}{8}(1-u)(3-u) \\ \phi_2(u) &= -\frac{1}{4}(1-u)^2 \end{aligned} \tag{23}$$

So, for twist 2 and 4 contributions we get

$$\Pi^{twist2+twist4} = Q_q < \bar{q}q > \{\int_0^1 \frac{\phi(u)du}{m_b^2-(p+uq)^2} - 4\int_0^1 \frac{(\phi_1(u)-\phi_2(u))du}{(m_b^2-(p+uq)^2)^2}[1+\frac{2m_b^2}{(m_b^2-(p+uq)^2)^2}]\} \quad (24)$$

In order to perform the double Borel transformation we rewrite denominator in the following way:

$$m_b^2-(p+uq)^2 = m_b^2-(1-u)p^2-(p+q)^2u$$

and applying the Wick rotation

$$m_b^2-(p+uq)^2 \rightarrow m_b^2+(1-u)p^2+(p+q)^2u$$

Using the exponential representation for the denominator we get

$$\Pi^{twist2+twist4} = e_q < \bar{q}q > e^{-m_b^2(\frac{1}{M_1^2}+\frac{1}{M_2^2})}[\phi(\frac{M_1^2}{M_1^2+M_2^2})\frac{1}{M_1^2+M_2^2} - 4(\phi_1(\frac{M_1^2}{M_1^2+M_2^2})-\phi_2(\frac{M_1^2}{M_1^2+M_2^2})) \cdot (\frac{1}{M_1^2M_2^2}+\frac{m_b^2(M_1^2+M_2^2)}{M_1^4M_2^4})] \quad (25)$$

The mass of $B^*(D^*)$ and $B(D)$ mesons are practically equal. So, it is natural to take $M_1^2 = M_2^2$, and introduce new Borel parameter M^2 such that $M_1^2 = M_2^2 = 2M^2$. In this case the theoretical part of the sum rules become

$$\Pi^{theor} = \frac{3}{4\pi^2}\int_{m_b^2}^{s_0} dse^{-s\frac{1}{M^2}}[(Q_q-Q_b)(1-\frac{m_b^2}{s})+Q_b ln\frac{s}{m_b^2}]\frac{1}{4M^4} + Q_b < \bar{q}q > e^{-\frac{m_b^2}{M^2}}[1-\frac{m_0^2m_b^2}{M^4}+\frac{m_0^2}{6M^2}]\frac{1}{4M^4} + Q_q < \bar{q}q > (e^{-m_b^2/M^2}-e^{-s_0/M^2})[M^2\phi(\frac{1}{2}) - 4(1+\frac{m_b^2}{M^2})(\phi_1(1/2)-\phi_2(1/2)]\frac{1}{4M^4} \quad (26)$$

In the derivation of Eq. (26), we have subtracted the continuum and higher resonance states from the double spectral density. The details of this procedure are given in [13].

For constructing the sum rules we need the expression for the physical part as well. Saturating Eq.(1) by the lowest lying meson states, we have

$$\Pi_{\mu}^{phys} = \frac{< 0|\bar{q}\gamma_{\mu}b|B^{*} >< B^{*}|B\gamma >< B|\bar{b}i\gamma_{5}q|0 >}{(m_{B^{*}}^{2} - p^{2})(m_{B}^{2} - (p+q)^{2})} \tag{27}$$

These matrix elements are defined as

$$\begin{aligned} < 0|\bar{q}\gamma_{\mu}b|B^{*} > &= \epsilon_{\mu} f_{B^{*}} m_{B^{*}} && (28) \\ < B|\bar{b}i\gamma_{5}q|0 > &= \frac{f_{B} m_{B}^{2}}{m_{b}} && (29) \\ < B^{*}|B\gamma > &= \varepsilon_{\alpha\beta\rho\sigma} p_{\alpha} q_{\beta} \epsilon_{\rho}^{*} \epsilon_{\rho}^{*(\gamma)} h/m_{B} && (30) \end{aligned}$$

Here h is the dimensionless amplitude for the transition matrix element, ϵ_{μ} , and $m_{B^{*}}$ are the polarization four-vector and the mass of the vector particle respectively, f_{B} is the leptonic decay constant and m_{B} is the mass of the pseudoscalar particle, q_{β} and ϵ_{σ} are the photon momentum and the polarization vector. Applying the double Borel transformation we get for the physical part of the sum rules

$$\Pi^{phys} = f_{B^{*}} m_{B^{*}} f_{B} m_{B} \frac{h}{m_{b}} \frac{e^{-(m_{B^{*}}^{2} + m_{B}^{2})/2M^{2}}}{4M^{4}} \tag{31}$$

Note that the contribution of three-particle twist-4 operators are very small [4], and thus we neglect them (Fig. (1)). From Eqs.(26-30) we get the dimensionless coupling constant as

$$\begin{aligned} h &= \frac{m_{b}}{f_{B^{*}} m_{B^{*}} f_{B} m_{B}} e^{(m_{B^{*}}^{2} + m_{B}^{2})/2M^{2}} \\ &. \quad \{\frac{3}{4\pi^{2}} \int_{m_{b}^{2}}^{s_{0}} ds e^{-s\frac{1}{M^{2}}} [(Q_{q} - Q_{b})(1 - \frac{m_{b}^{2}}{s}) + Q_{b} ln \frac{s}{m_{b}^{2}}] \end{aligned}$$

$$
\begin{aligned}
+ \quad & < \bar{q}q > e^{-\frac{m_b^2}{M^2}}[Q_b(1 - \frac{m_0^2 m_b^2}{8M^4} + \frac{m_0^2}{6M^2}] \\
+ \quad & (e^{-m_b^2/M^2} - e^{-s_0/M^2})[Q_q \phi(\frac{1}{2})M^2 \\
- \quad & 4Q_q(1 + \frac{m_b^2}{M^2})(\phi_1(1/2) - \phi_2(1/2))]\}
\end{aligned} \tag{32}
$$

3 Numerical Analysis of the Sum rules

The main issue concerning of Eq. (32) is the determination of the dimensionless transition amplitude h. First,we give a summary of the parameters entering in the sum rules Eq. (32). The value of the magnetic susceptibility of the medium in the presence of external field was determined in [19,20]

$$\chi(\mu^2 = 1GeV^2) = -4.4GeV^{-2}$$

If we include the anomalous dimension of the current $\bar{q}\sigma_{\alpha\beta}q$, which is $(-4/27)$ at $\mu = m_b$ scale, we get

$$\chi(\mu^2 = m_b^2 = -3.4GeV^{-2}$$

and

$$< \bar{q}q >= -(0.26\, GeV)^3$$

The leptonic decay constants $f_{B(D)}$ and $f_{B^*(D^*)}$ are known from two-point sum rules related to $B(D)$ meson channels: $f_{B(D)} = 0.14\,(0.17)\ MeV$ [13,21] , $f_{B^*(D^*)} = 0.16\,(0.24)\ GeV$ [13,22,23,24], $m_b = 4.7\ GeV$, $m_u = m_d = 0$, $m_0^2 = (0.8 \pm 0.2)\ GeV^2$, $m_{B^*(D^*)} = 5.\ (2.007)\ GeV$ and $m_{B(D)} = 5.\ (1.864)\ GeV$, and for continuum threshold we choose $s_0^B(s_0^D) = 36\,(6)\ GeV^2$.

The value $\phi_1(u) - \phi_2(u)$ is calculated in [11]:

$$\phi_1(u) - \phi_2(u) = \frac{-1}{8}(1 - u^2)$$

From the asymptotic form of the photon wave function, given in Eq. (21), we get

$$\phi(1/2) = 3/2\chi \tag{33}$$

Having fixed the input parameters, it is necessary to find a range of M^2 for which the sum rule is reliable.The lowest value of M^2, according to QCD sum rules ideology, is determined by requirement that the power corrections are reasonably small. The upper bound is determined by the condition that the continuum and the higher states contributions remain under control.

In Fig. 2 we presented the dependence of h on M^2. From this figure it follows that the best stability region for h is 6 $GeV^2 \leq M^2 \leq 12$ GeV^2 , and thus we obtain

$$\begin{aligned} f_{B^{0*}} f_{B^0} h &= -0.1 \pm 0.02 \\ f_{B^{+*}} f_{B^+} h &= 0.2 \pm 0.02 \end{aligned} \tag{34}$$

Note that the variation of the threshold value from $36\,GeV^2$ to $40\,GeV^2$ changes the result by few percents. We see that the sign of the amplitudes for B^0 and B^+ are different. This is due to the fact that the main contribution to the theoretical part of the sum rules comes from the bare loop and the quark condensate in external field (last term in Eq. (32)). In $B^0(B^+)$ cases, both contributions have negative (positive) signs and therefore the sign of h is negative (positive). To get the dimensionless transition amplitude for the decay $D^* \to D\gamma$, it is sufficient to make the following replacements in Eq. (32):

$$m_b \to m_c,\ f_{B^*(B)} \to f_{D^*(D)}, \quad Q_b \to Q_c, \quad and \ \ s_{0\,B} \to s_{0D} \tag{35}$$

Performing the same calculations we get the best stability region for h as $2\ GeV^2 \leq M^2 \leq 4\ GeV^2$ (Fig. (3)), and we find

$$\begin{aligned} f_{D^{0*}} f_{D^0} h &= 0.12 \pm 0.02 \\ f_{D^{+*}} f_{D^+} h &= -0.04 \pm 0.01 \end{aligned} \tag{36}$$

The signs of the transition amplitudes for D_0 and D^+ meson decays are different as in the B-meson case.

Using the transiton amplitude "h", one can calculate the decay rates for $B^*(D^*) \to B(D)\gamma$, which can be tested experimentally. For the decay width for radiative decay $B^*(D^*) \to B(D)\gamma$, we get

$$\Gamma(B_0^* \to B_0\gamma) = 0.28\, KeV \tag{37}$$

$$\Gamma(B^{+\,*} \to B^+\gamma) = 1.20\, KeV \tag{38}$$

and

$$\Gamma(D_0^* \to D_0\gamma) = 14.40\, KeV \tag{39}$$

$$\Gamma(D^{+\,*} \to D^+\gamma) = 1.50\, KeV \tag{40}$$

$$\tag{41}$$

In order to compare the theoretical results with experimental data for D-meson decays, we need the values of the $D^* \to D\pi$ decays widths.We take these values from ref. [13]:

$$\Gamma(D^{*+} \to D^0\pi^+) = 32 \pm 5\ \ KeV \tag{42}$$

$$\Gamma(D^{*+} \to D^+\pi^0) = 15 \pm 2\ \ KeV \tag{43}$$

$$\Gamma(D^{*0} \to D_0\pi^0) = 22 \pm 2\ \ KeV \tag{44}$$

From eqs.(39-43), for the BR, we obtain :

$$\begin{aligned} BR((D_0^* \to D_0\gamma) &= 39\% \\ BR(D^{+\,*} \to D^+\gamma) &= 3\% \end{aligned} \tag{45}$$

These results are in agreement with the CLEO data [25], which are

$$\begin{aligned} BR((D_0^* \to D_0\gamma) &= (36.4 \pm 2.3 \pm 3.3)\% \\ BR(D^{+\,*} \to D^+\gamma) &= (1.1 \pm 1.4 \pm 1.6)\% \end{aligned}$$

We see that our predictions on branching ratio are in reasonable agreement with the experimental results.

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Figure Captions

Figure 1: Diagrams contributing to the correlation function 1. Solid lines represent quarks, wave lines external currents.

Figure 2: The dependence of the transition amplitude h on the Borel parameter square M^2. Solid line corresponds B^0 and dashed line to B^+ meson cases.

Figure 3: The same as in Fig.2 but for D meson case.