Study of heavy-light meson $B_{d,s} \to D_{d,s}L(L = P, V)$ decays within QCD factorization

Zhao M.F.

School of Physics
Henan Normal University

November 12, 2022

JHEP

Published for SISSA by Springer

Received: March 15, 2021
Revised: August 31, 2021
Accepted: September 30, 2021
Published: October 28, 2021

Probing new physics in class-I B-meson decays into heavy-light final states

Fang-Min Cai,[1] **Wei-Jun Deng,**[1] **Xin-Qiang Li**[2] **and Ya-Dong Yang**

Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, Hubei 430079, P.R. China

E-mail: caifangmin@mails.ccnu.edu.cn, dengweijun@mails.ccnu.edu.cn, xqli@mail.ccnu.edu.cn, yangyd@mail.ccnu.edu.cn

Abstract: With updated experimental data and improved theoretical calculations, several significant deviations are being observed between the Standard Model predictions and the experimental measurements of the branching ratios of $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} L^-$ decays, where L is a light meson from the set $\{\pi, \rho, K^{(*)}\}$. Especially for the two channels $\bar{B}^0 \to D^+ K^-$ and $\bar{B}^0_s \to D^+_s \pi^-$, both of which are free of the weak annihilation contribution, the deviations observed can even reach 4–5σ. Here we exploit possible new-physics effects in these class-I non-leptonic B-meson decays within the framework of QCD factorization. Firstly, we perform a model-independent analysis of the effects from twenty linearly independent four-quark operators that can contribute, either directly or through operator mixing, to the quark-level $b \to c\bar{u}d(s)$ transitions. It is found that, under the combined constraints from the current experimental data, the deviations observed could be well explained at the 1σ level by the new-physics four-quark operators with $\gamma^\mu(1-\gamma_5) \otimes \gamma_\mu(1-\gamma_5)$ structure, and also at the 2σ level by the operators with $(1+\gamma_5) \otimes (1-\gamma_5)$ and $(1+\gamma_5) \otimes (1+\gamma_5)$

As all the four quark flavors in $b \to c\bar{u}d(s)$ transitions are different from each other, these tree-level decays receive contributions from neither the penguin operators nor the penguin topology. There is also no color-suppressed tree topology in these class-I decays. At leading power in $\Lambda_{\mathrm{QCD}}/m_b$, these decays are dominated by the color-allowed tree topology that receives only vertex corrections, while interactions with the spectator antiquark and the weak annihilation topology are both power-suppressed [20]. In fact, noting that the weak annihilation topology contributes only to $\bar{B}^0 \to D^{(*)+}\pi^-$ and $\bar{B}_s \to D_s^{(*)+}K^-$, but not to $\bar{B}^0 \to D^{(*)+}K^-$ and $\bar{B}_s \to D_s^{(*)+}\pi^-$, one can use the ratios between the branching fractions of these two kinds of decays to probe the topology. Remarkably, the current experimental data shows already that the impact due to such a topology is negligible [37].

Decay mode	$\lvert b_1\rvert$	$\lvert a_1/(a_1+b_1)\rvert$	$\lvert a_1/(a_1+b_1)\rvert^{\mathrm{exp.}}$
$\bar{B}^0 \to D^+\pi^-$	$0.019^{+0.051}_{-0.051}$	0.982 ± 0.056	$1.040^{+0.022}_{-0.022}$
$\bar{B}^0 \to D^{*+}\pi^-$	$0.017^{+0.065}_{-0.064}$	0.984 ± 0.075	$1.016^{+0.031}_{-0.032}$
$\bar{B}^0 \to D^+\rho^-$	$0.015^{+0.038}_{-0.038}$	0.987 ± 0.043	
$\bar{B}^0 \to D^{*+}\rho^-$	$0.015^{+0.045}_{-0.044}$	0.986 ± 0.050	
$\bar{B}_s^0 \to D_s^+K^-$	$0.026^{+0.068}_{-0.068}$	0.976 ± 0.072	$1.003^{+0.021}_{-0.020}$
$\bar{B}_s^0 \to D_s^{*+}K^-$	$0.025^{+0.095}_{-0.095}$	0.977 ± 0.106	$1.048^{+0.043}_{-0.046}$

Decay mode	LO	NLO	NNLO	NNLO$^{\#}$	Ref. [36]	Ref. [38]	Exp. [7, 8]
$\bar{B}^0 \to D^+\pi^-$	4.20	$4.45^{+0.25}_{-0.40}$	$4.58^{+0.22}_{-0.38}$	$4.74^{+0.61}_{-0.69}$	$3.93^{+0.43}_{-0.42}$		2.65 ± 0.15
$\bar{B}^0 \to D^{*+}\pi^-$	3.77	$4.00^{+0.29}_{-0.40}$	$4.13^{+0.27}_{-0.39}$	$4.26^{+0.75}_{-0.80}$	$3.45^{+0.53}_{-0.50}$		2.58 ± 0.13
$\bar{B}^0 \to D^+\rho^-$	10.98	$11.64^{+0.88}_{-1.18}$	$11.96^{+0.82}_{-1.15}$	$12.28^{+1.40}_{-1.63}$	$10.42^{+1.24}_{-1.20}$		7.6 ± 1.2
$\bar{B}^0 \to D^{*+}\rho^-$	10.32	$10.95^{+1.40}_{-1.55}$	$11.28^{+1.40}_{-1.56}$	$11.61^{+1.88}_{-2.01}$	$9.24^{+0.72}_{-0.71}$		6.0 ± 0.8
$\bar{B}^0 \to D^+K^-$	3.18	$3.37^{+0.17}_{-0.29}$	$3.48^{+0.14}_{-0.28}$		$3.01^{+0.32}_{-0.31}$	3.26 ± 0.15	2.19 ± 0.13
$\bar{B}^0 \to D^{*+}K^-$	2.82	$3.00^{+0.20}_{-0.29}$	$3.10^{+0.19}_{-0.28}$		$2.59^{+0.39}_{-0.37}$	$3.27^{+0.39}_{-0.34}$	2.04 ± 0.47
$\bar{B}^0 \to D^+K^{*-}$	5.48	$5.80^{+0.48}_{-0.62}$	$5.94^{+0.46}_{-0.61}$		$5.25^{+0.65}_{-0.63}$		4.6 ± 0.8
$\bar{B}_s^0 \to D_s^+\pi^-$	4.23	$4.49^{+0.27}_{-0.41}$	$4.61^{+0.23}_{-0.39}$		$4.39^{+1.36}_{-1.19}$	4.42 ± 0.21	3.23 ± 0.18
$\bar{B}_s^0 \to D_s^{*+}\pi^-$	3.51	$3.73^{+0.88}_{-0.84}$	$3.84^{+0.90}_{-0.85}$		$2.24^{+0.56}_{-0.50}$	$4.30^{+0.90}_{-0.80}$	$2.4^{+0.7}_{-0.6}$
$\bar{B}_s^0 \to D_s^+K^-$	3.21	$3.41^{+0.18}_{-0.30}$	$3.52^{+0.15}_{-0.29}$	$3.69^{+0.60}_{-0.65}$	$3.34^{+1.04}_{-0.90}$		2.41 ± 0.16

QCD factorization for exclusive non-leptonic B-meson decays: general arguments and the case of heavy–light final states

M. Beneke [a,*], G. Buchalla [b], M. Neubert [c], C.T. Sachrajda [d]

(a)

Application of the light-front holographic wavefunction for heavy-light pseudoscalar meson in $B_{d,s} \to D_{d,s} P$ decays

Qin Chang [a,b,*], Shuai Xu [a], Lingxin Chen [a]

(b)

Two-body non-leptonic heavy-to-heavy decays at NNLO in QCD factorization

Tobias Huber,[a] Susanne Kränkl[a] and Xin-Qiang Li[b]

(c)

(a)*Nuclear Physics B* 591(2000)313 − 418,
(b)*Nuclear Physics B* 921(2017)454 − 471,
(c)*JHEP* 09(2016)112;

衰变振幅表达式

- **effective weak Hamiltonian**
  effective weak Hamiltonian responsible for $B_{d,s} \to DL$ decay induced by $b \to c\bar{u}q(q = s, d)$

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s} V_{cb} V_{uq}^* \Big[C_1(\mu) Q_1(\mu) + C_2(\mu) Q_2(\mu) \Big] + \text{h.c.}, \quad (1)$$

$$Q_1 = (\bar{c}_\alpha b_\alpha)_{V-A} (\bar{q}_\beta u_\beta)_{V-A}, \qquad Q_2 = (\bar{c}_\alpha b_\beta)_{V-A} (\bar{q}_\beta u_\alpha)_{V-A}, \quad (2)$$

衰变振幅表达式

- **衰变振幅在QCD 因子化框架下的表达式**

  有效算符的强子矩阵元$\langle M_1 M_2|O_i(\mu)|B\rangle$，对于本文所考虑的$B$介子两体非轻弱衰变过程，在重夸克极限下，用QCD因子化公式来计算

$$\langle M_1 M_2|Q_i|B\rangle = \sum_j F_j^{B\to M_1} f_{M_2} \int dy\, T_{ij}^I(y)\, \varphi_{M_2}(y)\ , \tag{3}$$

  包括领头级贡献，和顶点修正图，旁观者散射等非因子化效应的贡献，并且考虑完整的手征增强的幂次修正的贡献，B介子两体非轻弱衰变的振幅的表达式可以写成

$$\mathcal{A}(B\to M_1 M_2) = \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \sum_i v_q \alpha_i(\mu) \langle M_1 M_2|Q_i|B\rangle_F, \tag{4}$$

衰变振幅表达式

重夸克极限下，QCD因子化方法的系数α_i 可以写成，

$$\alpha_i(M_1M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2) + \frac{C_{i\pm1}}{N_c}\frac{C_F\alpha_s}{4\pi}\left[V_i(M_2) + \frac{4\pi^2}{N_c}H_i(M_1M_2)\right], \quad (5)$$

LCDAs

$$M_B = -\frac{if_B}{4}[(\not p_B + m_B)\gamma_5]\Phi_B(\xi), \tag{6}$$

$$M_1 = M^D_{\alpha\beta} = +\frac{if_D}{4}\left(\not l\gamma_5\Phi_D(x) - m_D\gamma_5\phi_D(x)\right)_{\alpha\beta}, \tag{7}$$

$$M_2 = M^P_{\alpha\beta} = \frac{if_P}{4}\left(\not p\gamma_5\Phi_P(x) - \mu_P\gamma_5\frac{\not k_2\not k_1}{k_2\cdot k_1}\phi_p(x)\right)_{\alpha\beta}, \tag{8}$$

$$(M^V_{\parallel})_{\alpha\beta} = -\frac{if_V}{4}\left(\not p\Phi_V(x) - \frac{m_V f^{\perp}_V}{f_V}\frac{\not k_2\not k_1}{k_2\cdot k_1}\phi_v(x)\right)_{\alpha\beta}, \tag{9}$$

$$M^S_{\alpha\beta} = \frac{f_S}{4}\left(\not p\Phi_S(x) + \mu_S\frac{\not k_2\not k_1}{k_2\cdot k_1}\phi_s(x)\right)_{\alpha\beta}, \tag{10}$$

衰变振幅表达式

The hard-spectator corrections can be written as($B \to DP$)

$$\mathcal{H}_i = if_B f_{M_1} f_{M_2} \pi \alpha_s \frac{\Phi_B(\xi)}{\xi}\left(1-r_D^2\right)\left\{-\Phi_{D1}(y)\Phi_{P2}(x)\left[\frac{r_D^2+1}{\bar{x}\bar{y}}-\frac{2r_D^2}{x\bar{y}}\right]+\phi_{D1}(y)\Phi_{P2}(x)\left[\frac{r_D}{\bar{x}\bar{y}}-\frac{r_D}{x\bar{y}}\right]\right\} \tag{11}$$

for $i = 1-4, 9, 10,$

$$\mathcal{H}_i = if_B f_{M_1} f_{M_2} \pi \alpha_s \frac{\Phi_B(\xi)}{\xi}\left(1-r_D^2\right)\left\{\Phi_{D1}(y)\Phi_{P2}(x)\left[\frac{2r_D^2}{\bar{x}\bar{y}}-\frac{1+r_D^2}{x\bar{y}}\right]-\phi_{D1}(y)\Phi_{P2}(x)\left[\frac{r_D}{\bar{x}\bar{y}}-\frac{r_D}{x\bar{y}}\right]\right\} \tag{12}$$

for $i = 5, 7,$

$$\mathcal{H}_i = 0; \quad \mathit{for}\ i = 6, 8, \tag{13}$$

where $r_D = m_D/m_B$, $\bar{x} = 1-x$, $\bar{y} = 1-y$.

for $B \to DV$,$\mathcal{H}_i(DV) = \mathcal{H}_i(DP)$ $i = 1-4, 9, 10,$

$\mathcal{H}_i(DV) = -\mathcal{H}_i(DP)$ $i = 5, 7,$

衰变振幅表达式

$B_q \to D_q L$ decays:

$$\mathcal{A}\left(\bar{B}^0_{(s)} \to D^+_{(s)}\pi^-\right) = A_{D^+\pi^-} V_{cb} V^*_{ud} \alpha_1 \tag{14}$$

$$\mathcal{A}\left(\bar{B}^0_{(s)} \to D^+_{(s)}K^-\right) = A_{D^+K^-} V_{cb} V^*_{us} \alpha_1 \tag{15}$$

$$\mathcal{A}\left(\bar{B}^0_{(s)} \to D^+_{(s)}\rho^-\right) = A_{D^+\rho^-} V_{cb} V^*_{ud} \alpha_1 \tag{16}$$

$$\mathcal{A}\left(\bar{B}^0_{(s)} \to D^+_{(s)}K^{*-}\right) = A_{D^+K^{*-}} V_{cb} V^*_{us} \alpha_1 \tag{17}$$

输入参数

光前夸克模型下计算的形状因子、盖根保尔矩和衰变常数(in units of MeV)

$$f_{D^+} = 204.6, \quad f_{D_s^+} = 253.7, \quad f_{B_{u,d}} = 186 \pm 7,$$

$$F_0^{B\to D} = 0.7, \quad F_0^{B_S\to D_s} = 0.69, \quad f_{B_s} = 224 \pm 9,$$

$$D\,meson \quad a_0 = 1, \quad a_1 = 0.574, \quad a_2 = 0.106, \quad a_3 = 0.017,$$

$$D_s\,meson \quad a_0 = 1, \quad a_1 = 0.483, \quad a_2 = 0.025, \quad a_3 = -0.023,$$

数值结果

Table: The experimental results and theoretical predictions for $|\alpha_1|$ with and without the HSS corrections taken into account.

Decay modes	$T+V$	$T+V+HSS$	$T+V$[1]	$T+V+HSS$[1]	NLO[2]	NNLO[2]	Exp.[2]
$\|\alpha_1(\bar{B}_d^0 \to D^+K^-)\|$	1.030	1.027	1.053	1.049	$1.054^{+0.022}_{-0.019}$	$1.070^{+0.010}_{-0.013}$	0.87 ± 0.06
$\|\alpha_1(\bar{B}_d^0 \to D^+\pi^-)\|$	1.031	1.028	1.054	1.051	$1.054^{+0.022}_{-0.020}$	$1.073^{+0.012}_{-0.014}$	0.89 ± 0.05
$\|\alpha_1(\bar{B}_s^0 \to D_s^+K^-)\|$	1.030	1.025	1.053	1.050			
$\|\alpha_1(\bar{B}_s^0 \to D_s^+\pi^-)\|$	1.031	1.026	1.054	1.051			
$\|\alpha_1(\bar{B}_d^0 \to D^+K^{*-})\|$	1.030	1.027			$1.054^{+0.022}_{-0.019}$	$1.072^{+0.012}_{-0.014}$	0.99 ± 0.09
$\|\alpha_1(\bar{B}_d^0 \to D^+\rho^-)\|$	1.031	1.028			$1.054^{+0.022}_{-0.019}$	$1.072^{+0.012}_{-0.014}$	0.91 ± 0.08
$\|\alpha_1(\bar{B}_s^0 \to D_s^+K^{*-})\|$	1.030	1.026					
$\|\alpha_1(\bar{B}_s^0 \to D_s^+\rho^-)\|$	1.031	1.027					

数值结果

Table: The branching fractions (in units of 10^{-3}) of $B_{d,s} \to DL$ decays .

Decay modes	NF	$T+V$	$T+V+H$	*FM Cai* [1]	Ref.[2] [2]	Exp
$\bar{B}_d^0 \to D^+K^-$	0.318	0.324	$0.322^{+0.015+0.021}_{-0.011-0.020}$	0.318	$0.301^{+0.032}_{-0.031}$	0.208 ± 0.008
$\bar{B}_d^0 \to D^+\pi^-$	4.195	4.276	$4.252^{+0.188+0.467}_{-0.133-0.442}$	4.20	$3.93^{+0.43}_{-0.42}$	2.56 ± 0.13
$\bar{B}_s^0 \to D_s^+K^-$	0.314	0.319	$0.316^{+0.014+0.021}_{-0.010-0.020}$	0.321	$0.334^{+0.104}_{-0.090}$	0.241 ± 0.016
$\bar{B}_s^0 \to D_s^+\pi^-$	4.138	4.217	$4.182^{+0.185+0.459}_{-0.131-0.435}$	4.23	$4.39^{+1.36}_{-1.19}$	2.85 ± 0.18
$\bar{B}_d^0 \to D^+K^{*-}$	0.488	0.497	$0.494^{+0.022+0.039}_{-0.016-0.038}$	0.548	$0.525^{+0.065}_{-0.063}$	0.46 ± 0.08
$\bar{B}_d^0 \to D^+\rho^-$	9.79	9.977	$9.927^{+0.439+0.382}_{-0.310-0.375}$	10.98	$10.42^{+1.24}_{-1.20}$	7.6 ± 1.2
$\bar{B}_s^0 \to D_s^+K^{*-}$	0.482	0.491	$0.487^{+0.022+0.039}_{-0.016-0.038}$			
$\bar{B}_s^0 \to D_s^+\rho^-$	9.661	9.845	$9.779^{+0.433+0.376}_{-0.306-0.369}$			

[1] JHEP 10 (2021) 235

[2] JHEP 09 (2016) 112

数值结果

Table: The branching fractions (in units of 10^{-3}) of $B_{d,s} \to DL$ decays .

Decay modes	$T+V$	$T+V+H$	$\lvert\frac{H}{T+V+H}\rvert$
$\bar{B}_d^0 \to D^+ K^-$	0.324	$0.322^{+0.015+0.021}_{-0.011-0.020}$	0.006
$\bar{B}_d^0 \to D^+ \pi^-$	4.276	$4.252^{+0.188+0.467}_{-0.133-0.442}$	0.006
$\bar{B}_s^0 \to D_s^+ K^-$	0.319	$0.316^{+0.014+0.021}_{-0.010-0.020}$	0.009
$\bar{B}_s^0 \to D_s^+ \pi^-$	4.217	$4.182^{+0.185+0.459}_{-0.131-0.435}$	0.009
$\bar{B}_d^0 \to D^+ K^{*-}$	0.497	$0.494^{+0.022+0.039}_{-0.016-0.038}$	0.006
$\bar{B}_d^0 \to D^+ \rho^-$	9.977	$9.927^{+0.439+0.382}_{-0.310-0.375}$	0.005
$\bar{B}_s^0 \to D_s^+ K^{*-}$	0.491	$0.487^{+0.022+0.039}_{-0.016-0.038}$	0.008
$\bar{B}_s^0 \to D_s^+ \rho^-$	9.845	$9.779^{+0.433+0.376}_{-0.306-0.369}$	0.007

总结

在QCD因子化框架下，对重轻介子衰变过程进行了计算，其中除了树图和顶角修正振幅的贡献还考虑了旁观者散射振幅的贡献；从数据表格中我们可以发现幂次压低的旁观者散射对振幅大约有-0.4%的贡献；对$B \to DL$衰变理论预言存在着改善，但由于旁观者散射贡献太小，衰变分支比仍然比实验上给的结果大。

谢谢！

Q. Chang, S. Xu and L. Chen, Nucl. Phys. B **921** (2017), 454-471 doi:10.1016/j.nuclphysb.2017.06.002 [arXiv:1805.02011 [hep-ph]].

T. Huber, S. Kränkl and X. Q. Li, JHEP **09** (2016), 112 doi:10.1007/JHEP09(2016)112 [arXiv:1606.02888 [hep-ph]].