\[ B \to D^{(*)} \] transitions in a quark model

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We propose a constituent quark model to evaluate heavy decay constants and form factors relevant for \( B \to D^{(*)} \) semileptonic transitions. We show that the model reproduces the scaling laws dictated by the spin-flavour symmetry in the heavy quark limit and describes quite well the experimental data.

I. INTRODUCTION

The study of exclusive charmed semileptonic decays of B mesons is of primary importance to extract one of the free parameters of the Standard Model: the absolute value of the Cabibbo-Kobayashi-Maskawa matrix element, \( |V_{cb}| \). The extraction is based on the prediction of the Heavy Quark Effective Theory (HQET) which fix an absolute normalization, at zero recoil point, of the form factor which survives in the limit of infinite quark masses. Moreover, it is possible to show that differently from \( B \to D \ell \nu \) process the \( B \to D^* \ell \nu \) decay doesn’t receive \( 1/m_Q \) corrections at zero recoil point. This facts allow us to extract \( |V_{cb}| \) from the differential partial decay width for the \( B \to D^* \ell \nu \) process in a nearly model independent way.

In this paper we will study the \( B \to D^{(*)} \ell \nu \) processes from a different point of view. We propose a very simple constituent quark model to evaluate heavy decay constants and heavy-to-heavy form factors. They exhibit the scaling laws dictated by the HQET at leading order and describe in a satisfactory way the experimental data. To study the semileptonic transitions between the heavy mesons \( B \) and \( D^{(*)} \) and to compute the relevant hadronic matrix elements we use the ideas presented in the papers in Ref. devoted to study heavy to light semileptonic and rare B transitions. In that papers, the heavy meson \( B \) is described as a \( b \bar{q} \) \( (q\in\{u,d\}) \) bound state and the corresponding wave function, \( \psi(k) \), is obtained by solving a QCD relativistic potential model. Here, we adopt a different point of view. As in \( \text{ Ref. } \), we describe the involved (heavy) mesons as bound state of a heavy quark and a light anti-quark but for the wave functions we assume their mathematical form and we fix the free parameters by comparing model predictions and experimental data, when available (see after).

The paper is organized as follows. In the next section we introduce our constituent quark model, heavy decay constants and heavy-to-heavy form factors are evaluated in section II. The section III is devoted to discuss the heavy quark limit for decay constants and form factors. Numerical results and conclusions are collected in section IV.

II. THE MODEL

We describe any heavy meson \( H(Q\bar{q}) \), with \( Q\in\{b,c\} \), by introducing the matrix

\[
H = \frac{1}{\sqrt{3}} \psi_H(k) \sqrt{\frac{m_Q m_q}{m_Q m_Q + q_1 \cdot q_2}} \frac{q_1 + m_Q}{2m_Q} \frac{-q_2 + m_q}{2m_q},
\]

where \( m_Q \) (\( m_q \)) stands for the heavy (light) quark mass; \( q_1^\mu \), \( q_2^\mu \) their corresponding 4–momenta (cf. Fig. I). With \( \psi_H(k) \) we indicate the meson’s wave function and the factors are chosen to satisfy the following relations

\[
\langle H| \psi_H(k) \rangle = \text{Tr}\{(-\gamma_0 H^\dagger \gamma_0) H\} = 2 m_H, \]

\[
\int \frac{d^3k}{(2\pi)^3} |\psi_H(k)|^2 = 2 m_H.
\]

The meson-constituent quarks vertex, \( \Gamma \), is given by

\[
\Gamma = -i\gamma_5 = \Gamma_P \quad \text{for pseudoscalar mesons}
\]

\[
\Gamma = \varepsilon_\mu \left[\gamma_\mu - \frac{q_1^\mu - q_2^\mu}{m_H + m_Q + m_q}\right] = \Gamma_V(\varepsilon, q_1, q_2) \quad \text{for vector mesons}
\]

where \( \varepsilon \) is the polarization 4–vector of the (vector) meson \( H \). In any \( HQ\bar{q} \) vertex we assume the 4–momentum conservation, i.e. \( q_1^\mu + q_2^\mu = p^\mu \), the \( H \) meson 4–momentum. Therefore, if we choose \( q_1^\mu = (E_Q, \vec{k}) \), and \( q_2^\mu = (E_q, -\vec{k}) \),
i.e. the H rest frame, we have \((k \equiv |\vec{k}|)\)

\[
E_Q + E_q = \sqrt{m_Q^2 + k^2} + \sqrt{m_q^2 + k^2} = m_H.
\]  

(5)

which can be read as the definition of a running heavy quark mass, as was done in Ref. [7]. In fact, the Eq. (5) with the constraint \(m_Q(k) \geq 0\) gives the relation

\[
0 \leq k \leq K_M \equiv \frac{m_H^2 - m_q^2}{2m_H}
\]

(6)

on the loop momentum \(k\)

\[
\int \frac{d^3k}{(2\pi)^3}.
\]

(7)

Let us now write down the remaining rules for the computation of the hadronic matrix elements in the framework of this model:

a) for the weak hadronic current, \(\bar{q}_2 \Gamma^\mu q_1\), one puts the factor

\[
\sqrt{\frac{m_{q_1}}{E_{q_1}}} \sqrt{\frac{m_{q_2}}{E_{q_2}}} \Gamma^\mu,
\]

(8)

where \(\Gamma^\mu\) is some combination of Dirac matrices;

b) for each quark loop, in addition to the integration in Eq. (7), one puts a colour factor of 3 and performs a trace over Dirac matrices.

### III. LEPTONIC DECAY CONSTANTS AND B → D(+) SEMILEPTONIC TRANSITIONS

In this section we introduce heavy decay constants and semileptonic form factor for heavy-to-heavy transitions and we give their expressions in the framework of our model.

Using the rules introduced in the previous section we immediately get the expressions for the heavy meson decay constants. The pseudoscalar case was obtained and discussed in Ref. [7], for future convenience, we report the resulting expression for the B meson:

\[
f_B = \frac{\sqrt{3}}{2\pi^2 m_B^2} \int_0^{K_M} dk k^2 \psi_B(k) \frac{(m_b + m_c)(m_q m_q + q_1 \cdot q_2)}{\sqrt{E_b E_q (m_b m_q + q_1 \cdot q_2)}}.
\]

(9)

Moreover, we have evaluate the vector heavy meson decay constant, which is defined by

\[
< 0|V_\mu|H^+(p, \varepsilon) > = m_{H^+} f_{H^+} \varepsilon_\mu.
\]

(10)

In particular, if we consider the \(B^*\) meson, we obtain

\[
f_{B^*} = \frac{\sqrt{3}}{2\pi^2 m_{B^*}} \int_0^{K_M} dk \frac{k^2 \psi_{B^*}(k)}{\sqrt{E_b E_q (m_b m_q + q_1 \cdot q_2)}} \left( m_b m_q + q_1 \cdot q_2 \right) - \frac{2}{3} \frac{k^2 m_{B^*}}{m_{B^*} + m_b + m_q}.
\]

(11)

#### A. B → D and B → D* form factors

The same rules allow us to evaluate the matrix element \(< D(p') | \bar{q}_2 \gamma_\mu b | B(p) >\) relevant to the weak semileptonic transition of B to D mesons. With reference to the graph in Fig. III and choosing the 4-momenta \(q_1\) and \(q_2\) as in the previous section and \(q_3^2 = (E_c, \vec{k} - \vec{q})\), we get

\[
< D(p') | \bar{q}_2 \gamma_\mu b | B(p) = \int \frac{d^3k}{(2\pi)^3} \psi_D(k) \psi_B(k) \sqrt{\frac{m_q m_b}{m_q m_b + q_1 \cdot q_2}} \sqrt{\frac{m_b m_c}{m_b m_c + q_3 \cdot q_2}} \sqrt{\frac{m_q m_c}{m_q m_c + q_3 \cdot q_2}} \left( \frac{-q_2 + m_q}{2m_q} \frac{\Gamma_p}{\Gamma_p} \frac{q_3 + m_c}{2m_c} \gamma_\mu \frac{q_1 + m_b}{2m_b} \left( \frac{\Gamma_p}{\Gamma_p} - \frac{q_2 + m_q}{2m_q} \right) \right).
\]

(12)
with

\[
\begin{align*}
\phi &\leq 2\pi \\
f(k,|\vec{q}|) &= \frac{2\sqrt{m_D + q^2}}{2k|\vec{q}|} \sqrt{k^2 + m_b^2 - (m_D^2 + m_q^2)}
\end{align*}
\]

In the previous equation the integration domain \( D \) is fixed enforcing the energy conservation both in the initial and final quarks-meson vertexes. This can be done introducing, in addition to the beauty running mass (cf. Eq. (5)), the charm running mass \( m_c(k) \) for which \( m_c(k) \geq 0 \). After some algebra the physical domain \( D \) is found to be given by

\[
\begin{align*}
\text{Max}(0, k_-) &\leq k \leq \text{Min}(K_M, k_+) \\
\text{Max}(-1, f(k,|\vec{q}|)) &\leq \cos(\theta) \leq +1 \\
0 &\leq \phi \leq 2\pi
\end{align*}
\]

\( \phi \) and \( \theta \) are the azimuthal and the polar angles, respectively. Note that we have chosen the \( z \)-axis along the direction of \( \vec{q} \), the (tri-)momentum of the W boson (cf. Fig. 1).

The Eq. (12) allows us to immediately extract the form factors \( f_{\pm}(q^2) \) defined by

\[
< D(p')|\bar{c}\gamma_\mu b|B(p) > = f_+(q^2)(p_\mu + p'_\mu) + f_-(q^2)(p_\mu - p'_\mu).
\]

The last matrix element relevant to charmed semileptonic decay of B mesons is usually written in terms of the following form factors

\[
< D^*(p', \varepsilon)|\bar{c}\gamma_\mu(1 - \gamma_5)b|B(p) > = 2q(q^2) \varepsilon^{\mu\rho\sigma\beta} \varepsilon^\ast_\rho p_\sigma p_\beta
\]

\[
- i \left\{ f(q^2) \varepsilon^\ast_\mu + (\varepsilon^\ast \cdot p) \left[ a_+(q^2) (p_\mu + p'_\mu) + a_-(q^2) (p_\mu - p'_\mu) \right] \right\},
\]

they are connected in our model to

\[
< D^*(p', \varepsilon)|\bar{c}\gamma_\mu(1 - \gamma_5)b|B(p) > = \int_D \frac{d^3k}{(2\pi)^3} \psi_D^\ast(k)\psi_B(k) \sqrt{\frac{m_q m_b}{m_q m_b + q_1 \cdot q_2}} \sqrt{\frac{m_q m_c}{m_q m_c + q_3 \cdot q_2}}
\]

\[
\frac{m_b m_c}{E_B E_c} \text{Tr} \left[ -\frac{\hat{q}_2 + m_q}{2m_q} (\Gamma_V(\varepsilon, q_3, q_2)^\dagger \frac{\hat{q}_3 + m_c}{2m_c} \gamma_\mu (1 - \gamma_5) \frac{\hat{q}_1 + m_b}{2m_b} (\Gamma_f) - \frac{\hat{q}_2 + m_q}{2m_q} \right].
\]

Also in this case the extraction of the form factors in Eq. (17) can be done using the same frame we adopt for the extraction of \( f_{\pm}(q^2) \). For the polarization vectors we use:

\[
\varepsilon^\mu(\lambda) = \begin{cases} 
(0, -1, 0, 0) & \lambda = 1 \\
(0, 0, 1, 0) & \lambda = 2 \\
(|\vec{q}|, 0, 0, -E_{D^\ast})/m_{D^\ast} & \lambda = L
\end{cases}
\]

where \( E_{D^\ast} = \sqrt{q^2 + m_{D^\ast}^2} \) represents the energy of the \( D^\ast \) meson.
IV. HEAVY QUARK LIMIT

In this section we discuss the Heavy Quark Limit for decay constants and form factors. We show that decay constants and heavy-to-heavy form factors satisfy the scaling laws predicted by HQET at leading order \cite{3}.

To show how the results of our model depend on the heavy quark mass, we need to specify the shape of the wave functions $\psi_H(k)$. We choose two possible forms, the gaussian-type, extensively used in literature (see for example \cite{8, 9})

$$\psi_H(k) = 4\pi^{3/4} \frac{m_H}{\omega_H^{3/2}} \exp \left\{ -\frac{k^2}{2\omega_H^2} \right\},$$  

(20)

and the exponential one

$$\psi_H(k) = 4\pi \frac{m_H}{\omega_H^{3/2}} \exp \left\{ -\frac{k}{\omega_H} \right\},$$  

(21)

which is able to fit the results of relativistic quark model \cite{10}. In our approach $\omega_H$ is a free parameter which should be fixed (cf. next section for details).

A. Heavy Decay Constants

To extract the heavy mass dependence from the decay constant, it is useful to define $x = (2\alpha k)/m_B$ in such a way the expressions in Eq. (9) and (11) can be formally written as

$$f_B(\ast) = \int_0^\alpha dx \psi_B(k(x)) F_B(\ast)(x, z),$$  

(22)

where $F_B(\ast)(x, z)$ have a very simple expressions for $z = 0$ ($z \equiv m_q/m_B$)

$$F_B(x, 0) = \frac{\sqrt{3}}{2} \frac{m_B^2}{8\pi^2\alpha^3} \frac{x^2(\alpha - x)}{\sqrt{\alpha(\alpha - x)(2\alpha - x)}},$$  

(23)

$$F_B(\ast, x, 0) = \frac{m_B^2}{8\sqrt{6}} \frac{x^2}{\pi^3\alpha^3} \frac{3(\alpha + \sqrt{\alpha(\alpha - x)}) - x}{\sqrt{2\alpha - x}} \left( \sqrt{\alpha + \sqrt{\alpha - x}} \right)$$  

(24)

The integral in Eq. (22), for $0 < \alpha \ll 1$ can be evaluated analytically, obtaining for the leading behaviour the following result

$$f_B(\ast) \simeq \begin{cases} 
\frac{1}{\sqrt{m_B}} \frac{\sqrt{6}\omega_H^3}{\pi^{3/4}} & \text{gaussian - type} \\
\frac{1}{\sqrt{m_B}} \frac{4\sqrt{3}\omega_H^3}{\pi} & \text{exponential - type}
\end{cases}$$  

(25)

in both cases in agreement with the scaling law predicted by the HQET.

B. $B \rightarrow D$ Form Factors

The same procedure applied to the heavy-to-heavy ($B \rightarrow D$) transitions allows us to find the scaling laws of the form factors $f_\pm$ defined in Eq. (10). As for decay constants, we can formally write

$$f_\pm(q^2) = \int_0^\alpha dx \psi_B(k(x)) \psi_D(k(x)) F_\pm(x, z, q^2),$$  

(26)

where, for $z = 0$, $x \ll 1$ and near the zero recoil point ($q^2 = q_{\text{max}}^2$)

$$F_\pm(x, 0, q^2)|_{q^2= q_{\text{max}}^2} \simeq \frac{x^2}{64\pi^2\alpha^3} \frac{m_D^2(m_D \pm m_B)}{(m_D \pm m_B)} \left( 1 - \frac{11}{12}(w - 1) \right).$$  

(27)
Here \( w = v \cdot v' \) with \( v \) and \( v' \) the four-velocities of the B and D mesons, respectively. Also in this case we can extract the dependence of the form factors from the heavy masses performing the integration in Eq. (28):

\[
f_{\pm}(q^2)|_{q^2 \gtrsim q^2_{\text{max}}} \simeq \frac{m_D \pm m_B}{2 \sqrt{m_D m_B}} \left\{ \begin{array}{ll}
2 \sqrt{2} \left( \frac{\omega_B \omega_D}{\omega_B^2 + \omega_D^2} \right)^{3/2} & \left( 1 - \frac{11}{12}(w - 1) \right) \\
8 \sqrt{\frac{\omega_B^3 \omega_D^3}{\omega_B + \omega_D}^3} & \left( 1 - \frac{11}{12}(w - 1) \right)
\end{array} \right. \\
\begin{array}{ll}
\text{gaussian - type} \\
\text{exponential - type}
\end{array}
\]

It should be observed that the terms in square brackets should be interpreted as the Isgur-Wise function, \( \xi(w) \), near to \( w = 1 \). Moreover, in the Heavy Quark Limit we should have \( \omega_B = \omega_D \) which implies the correct normalization, \( \xi(1) = 1 \), for both wave functions.

\[ \xi(w) = 1 - \frac{11}{12}(w - 1) + \frac{77}{96}(w - 1)^2 + o((w - 1)^3), \]

where the quadratic term, neglected in Eqs. (28), (31) and (32), is shown. The resulting Isgur-Wise function satisfies both the Bjorken Sum Rule (11)

\[ \rho^2 = -\xi'(1) = \frac{11}{12} \geq \frac{3}{4}, \]

and the lower bound on the curvature (12):

\[ \sigma^2 \equiv \xi''(1) = \frac{77}{48} \geq \frac{4}{5}\rho^2 \left( 1 + \frac{3}{4}\rho^2 \right) = \frac{99}{80}. \]
& Exp. or Lattice & our fit (exp.) & our fit (gauss.) \\ 
\hline
$f_D/f_B$ & $1.23 \pm 0.22$ [13] & 1.03 & 1.05 \\
$f_D$ & $300^{+150}_{-150} \pm 30$ MeV [1] & 145 MeV & 145 MeV \\
BR($B \to D\ell\nu$) & $(2.14 \pm 0.15)\%$ [1] & 2.04 % & 1.75 % \\
$f_B$ & 140 MeV & 139 MeV & 139 MeV \\
\hline
\end{tabular}

TABLE I: The experimental values [1] and Lattice result [13] for the decay constants used in the fit of the free parameters of the model. For the free parameter we assume $\omega = \omega^*$. Moreover, we use $|V_{cb}| = (41.3 \pm 1.5) \times 10^{-3}$ [1].

| Parameter | fitted values (exp.) | fitted values (gauss.) |
|-----------|----------------------|------------------------|
| $m_q$     | 311 MeV              | 269 MeV                |
| $\omega_B$ | 258 MeV              | 421 MeV                |
| $\omega_D$ | 255 MeV              | 347 MeV                |

TABLE II: The values for the free parameters of the model in correspondence of the best fit for both wave functions. The two sets of values are obtained for the exponential (exp.) and gaussian vertex (gauss.).

V. NUMERICAL RESULTS AND DISCUSSION

As we have seen in section [11], the heavy-to-heavy form factors can be easily extracted with the help of the Eqs. (12), (16), (17) and (18). Nevertheless, unlike for the decay constants, their analytical expressions are quite long, and, for the sake of brevity, we do not report them here.

As already discussed in the previous section, to evaluate numerically form factors and decay constants, we must fix the meson wave functions, $\psi_H(k)$. For the wave function we considered two possibilities: the gaussian and the exponential form. In both cases, for any heavy meson, $H$, we have one more free parameter, $\omega_H$. In order to determine the free parameters of the model we proceed as follows. We neglect differences between pseudoscalar and vector mesons in the vertex function, in other words we put $\omega_D = \omega_D^*$. Moreover, we neglect differences between $u$ and $d$ quark masses. In such a way the free parameters of the model are $\omega_B$, $\omega_D$ and $m_q$. They are adjusted by fitting the experimental values of $f_D$, BR($B \to D\ell\nu$) and the results of lattice simulation on the ratio $f_D/f_B$. The numerical results are collected in Tables I and II.

Comments about the results in Table I are in order. Let us start with decay constants. The model predicts large $1/m_c$ corrections for $f_D$ in such a way the predicted ratio $f_D/f_B$ violates strongly the heavy quark mass limit. However, in the allowed region for the parameters there is the possibility to fulfill both the heavy quark limit and the Lattice result but the values of the decay constants ($f_D \sim f_B \sim 140$ MeV) are predicted smaller than the ones obtained by Lattice simulations [13]. Regarding the $B \to D$ form factors, it should be observed that the experimental value for the BR($B \to D\ell\nu$) can be reproduced with $|V_{cb}| = (41.3 \pm 1.5) \times 10^{-3}$ [1]. However, when the exponential function is considered, the agreement becomes better as a consequence of the larger value predicted for $f_+(0)/(f_+(0) = 0.57 (0.51)$ for exponential (gaussian) vertex function). The same situation occurs if the differential partial decay width for the $B \to D^*\ell\nu$ is considered. In Figure 2, assuming the values in Table I, we plot $d\Gamma(B \to D^*\ell\nu)/dw$ in comparison with experimental data [2, 8]. In particular, the left (right) panel allows to compare model predictions and experimental data for the exponential (gaussian) vertex function. Both panels contain three curves corresponding to the predicted $d\Gamma(B \to D^*\ell\nu)/dw$ for the central, upper and lower $1\sigma$ values of $|V_{cb}|$ [1]. The agreement between model predictions and experimental data is quite good, a better agreement requires a smaller value of $|V_{cb}|$. In this respect, using exponential vertex function and a value of $|V_{cb}| = 38.7 \times 10^{-3}$ [2], the predicted $d\Gamma(B \to D^*\ell\nu)/dw$ is in very good agreement with experimental data from Babar [2].

In conclusion we have proposed a constituent quark model to describe heavy mesons. We showed that the model predictions on decay constants and form factors reproduce the scaling laws dictated by HQET at leading order in the heavy quark mass limit. For finite heavy quark masses the agreement with experimental data is quite good.
FIG. 2: Predicted ranges for $d\Gamma(B \to D^*\ell\nu)/dw$ compared to data. Solid boxes (triangles) refer to $B^0 \to D^{*+}\ell^-\bar{\nu}$ ($B^- \to D^{*0}\ell^-\bar{\nu}$) process [4]. Data points from BABAR [5] are displayed with stars. Solid lines refer to model predictions for exponential (left) and gaussian (right) in correspondence of $|V_{cb}| = (39.8, 41.3, 42.8) \times 10^{-3}$ [1].

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