One-particle inclusive $B_s \to \bar{D}_s X$ decays

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We discuss one-particle inclusive $B_s \to \bar{D}_s X$ decays using a QCD-based method already applied to $B \to \bar{D} X$. A link between the right charm nonperturbative form factors of the semileptonic decays and those of the nonleptonic decays is established. Our results are compatible with current experimental knowledge.

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I. INTRODUCTION

Some time ago, a QCD-based method was proposed to describe $B \to \bar{D} l \nu X$ decays, which relies on a short distance expansion (SDE) and on the heavy quark effective theory [1]. The nonperturbative form factors of the singlet operators were parametrized using the Isgur-Wise function. More recently this method was extended to one-particle inclusive nonleptonic B decays [2]. In this case, we have to perform a $1/N_C$ expansion, which allows to factorize the matrix elements. One of the goals of this work is to clarify the link between the matrix elements which were encountered in the semileptonic one-particle inclusive B decays [1] and those of the nonleptonic one-particle inclusive B decays encountered in [2]. In fact, we prove that these matrix elements are universal. We then apply this method to one-particle inclusive $B_s \to \bar{D}_s X$ and $B_s \to D_s X$ decays.

It is shown in [2] that the one-particle inclusive decays of a B meson into a vector D meson seem to be, in this framework, well understood whereas decays of a B meson into a pseudoscalar D are troublesome; i.e., the decay widths and spectra for $B \to \bar{D}^*/D^* X$ admixtures look to be described correctly, on the other hand, the predictions for $B \to \bar{D}/DX$ admixture decay widths and spectra do not reproduce the experimental data. Most troublesome is the fact that the spectra are not even described correctly for large transferred momentum. According to our method we expect to describe the experimental data for large transfered momentum particularly well.

Keeping in mind that some problems arose in the description of $B \to \bar{D}/DX$ decays, we apply the method developed for these decays to $B_s \to \bar{D}_s X$ and $B_s \to D_s X$ decays. The effective Hamiltonian is identical in both cases. One-particle inclusive $B_s \to \bar{D}_s X$ decay widths have been measured by ALEPH. There are measurements for semileptonic [3] as well as for nonleptonic [4] decays.

The decay rates we are computing can be used to study one-particle inclusive CP asymmetries in the B_s system [5], which would allow an extraction of the weak angle γ which is known to be difficult. This study of $B_s \to D_s X$ decays could also allow us to get a better understanding of the problems encountered in $B \to DX$ decays [2]. They are also interesting for experimental physics especially in the perspective of B factories as the presently available data on one-particle inclusive $B_s \to D_s X$ decays are sparse.

In the following section, we shall establish the link between the form factors of the semileptonic decays and those of the nonleptonic decays for the right charm $\bar{b} \to \bar{c}$ transition.

II. FROM SEMILEPTONIC TO NONLEPTONIC DECAYS

We consider right charm decays $B \to \bar{D} X$, i.e., $\bar{b} \to \bar{c}$ transitions. The central quantity in the semileptonic case as well as the nonleptonic case is the function G given by

$$G(M^2) = \sum_X |\langle B(p_B)|H_{eff}|\bar{D}(p_{\bar{D}})X\rangle|^2 (2\pi)^4 \times \delta^4(p_B - p_{\bar{D}} - p_X), \tag{1}$$

where $|X\rangle$ are momentum eigenstates with momentum p_X, H_{eff} is the relevant part of the weak Hamiltonian, and $M^2 = (p_B - p_{\bar{D}})^2$ is the invariant mass. The states $|X\rangle$ form a complete set, especially $|X\rangle$ can be the vacuum in the semileptonic case, e.g., $B \to \bar{D} l \nu$ contributes to $B \to \bar{D} l \nu X$. This function G is related to the decay rate under consideration by

$$d\Gamma(B \to \bar{D} X) = \frac{1}{2 m_B} d\Phi_{\bar{D}} G(M^2), \tag{2}$$

where $d\Phi_{\bar{D}}$ is the phase-space element of the final-state $\bar{D}$ meson. The relevant weak Hamiltonian is given by

$$H_{eff} = H_{eff}^{(sl)} + H_{eff}^{(nl)}, \tag{3}$$

where the semileptonic and nonleptonic pieces are given by

$$H_{eff}^{(sl)} = \frac{G_F}{\sqrt{2}} V_{cb} (\bar{b} c)_{V-A} (\bar{l} \nu)_{V-A} + \text{H.c.}, \tag{4}$$

$$\begin{aligned} H_{eff}^{(nl)} = {} & \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* ((\bar{b} c)_{V-A} (\bar{u} d)_{V-A} \\ & + (\bar{b} T^a c)_{V-A} (\bar{u} T^a d)_{V-A}) \\ & + \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* ((\bar{b} c)_{V-A} (\bar{c} s)_{V-A} \\ & + (\bar{b} T^a c)_{V-A} (\bar{c} T^a s)_{V-A}) + \text{H.c.}, \end{aligned} \tag{5}$$

where we have neglected the penguins and the Cabibbo suppressed operators. The function G can be written as

$$G(M^2)=\sum_X \int d^4x\langle B(p_B)|H_{eff}(x)|\overline{D}(p_{\overline{D}})X\rangle \times\langle \overline{D}(p_{\overline{D}})X|H_{eff}(0)|B(p_B)\rangle. \tag{6}$$

In the semileptonic case we can trivially factorize $G(M^2)$ and obtain

$$\begin{aligned}G^{Lep}(M^2)=&\frac{G_F^2}{2}|V_{cb}|^2\sum_X (2\pi)^4\delta^4(M-p_X)\\ &\times\langle 0|(\overline{l}\gamma^\mu(1-\gamma_5)\nu)(\overline{\nu}\gamma^\nu(1-\gamma_5)l)|0\rangle\\ &\times\langle B(p_B)|(\overline{b}\gamma_\mu(1-\gamma_5)c)|\overline{D}(p_{\overline{D}})X\rangle\\ &\times\langle \overline{D}(p_{\overline{D}})X|(\overline{c}\gamma_\nu(1-\gamma_5)b)|B(p_B)\rangle.\end{aligned} \tag{7}$$

The next steps are to insert heavy quark fields in the effective Hamiltonian and considering m_b and m_c as large scales, to perform a SDE as it has been explained in [1]. In the leading order of the SDE, $G^{Lep}(M^2)$ reads

$$\begin{aligned}G^{Lep}(M^2)=&\frac{G_F^2}{2}|V_{cb}|^2P^{Lep}_{\mu\nu}(M)\\ &\times\sum_X \langle B(v)|[\overline{b}_v\gamma^\mu(1-\gamma_5)c_{v'}]|\overline{D}(v')X\rangle\\ &\times\langle \overline{D}(v')X|[\overline{c}_{v'}\gamma^\nu(1-\gamma_5)b_v]|B(v)\rangle,\end{aligned} \tag{8}$$

where v is the velocity of the B meson, v' is the velocity of the $\overline{D}$ meson, and $P^{Lep}_{\mu\nu}$ is a tensor originating from the contraction of the lepton fields in the effective Hamiltonian. This tensor is given by

$$P^{Lep}_{\mu\nu}(M)=A(M^2)(M^2g_{\mu\nu}-M_\mu M_\nu)+B(M^2)M_\mu M_\nu. \tag{9}$$

Neglecting the lepton masses, we obtain at tree level

$$A(M^2)=-\frac{1}{3\pi}\Theta(M^2) \quad \text{and} \quad B(M^2)=0. \tag{10}$$

We now consider the nonleptonic case. The nonleptonic case is more complex because two transitions are possible: the right charm $\overline{b}\to\overline{c}$ transition and the wrong charm transition $\overline{b}\to c$. The wrong charm transition was treated in [2] and we will not come back to this issue, since this channel is extremely suppressed in the semileptonic case and was neglected in [1] and our aim in this section is strictly to establish the link between the right charm semileptonic and nonleptonic decays. Another difficulty is that factorization can only be performed in the $1/N_C$ limit. This concept is known to be valuable for nonleptonic exclusive B mesons decays [6]. In this limit the octet operators vanish. Thus, we obtain

$$\begin{aligned}G^{NL}(M^2)=&\frac{G_F^2}{2}|V_{cb}V^*_{q_1q_2}|^2|C_1|^2\sum_X\sum_{X'} (2\pi)^4\delta^4(M-p_X\\ &-p_{X'})\langle B(p_B)|(\overline{b}\gamma_\mu(1-\gamma_5)c)|\overline{D}(p_{\overline{D}})X\rangle\\ &\times\langle 0|(\overline{q_1}\gamma^\mu(1-\gamma_5)q_2)|X'\rangle\\ &\times\langle X'|(\overline{q_2}\gamma^\nu(1-\gamma_5)q_1)|0\rangle\\ &\times\langle \overline{D}(p_{\overline{D}})X|(\overline{c}\gamma_\nu(1-\gamma_5)b)|B(p_B)\rangle,\end{aligned} \tag{11}$$

where the q_i's stand for quarks. We see that assuming that X and X' are disjoint, which is certainly the case in the leading order of the $1/N_C$ limit, we can at once apply the completeness relation for X' and we just find ourselves in the same situation as in the semileptonic case.

For the quark transition $b\to c\overline{u}d$ we have $q_1=u$ and $q_2=d$, i.e., we have two light quarks whose masses can be neglected just as the one of the leptons in the semileptonic case. We obtain

$$P^{NL}_{\mu\nu}(M)=N_CP^{Lep}_{\mu\nu}(M), \tag{12}$$

where N_C is the color number, and

$$\begin{aligned}G^{NL}(M^2)=&\frac{G_F^2}{2}|V_{cb}V^*_{ud}|^2P^{NL}_{\mu\nu}(M)\\ &\times\sum_X \langle B(v)|[\overline{b}_v\gamma^\mu(1-\gamma_5)c_{v'}]|\overline{D}(v')X\rangle\\ &\times\langle \overline{D}(v')X|[\overline{c}_{v'}\gamma^\nu(1-\gamma_5)b_v]|B(v)\rangle.\end{aligned} \tag{13}$$

The transition $b\to c\overline{c}s$ can be treated in the same fashion. In that case the mass of the c quark in the loop cannot be neglected. We obtain

$$P^{NL}_{\mu\nu}(M)=A(M^2)(M^2g_{\mu\nu}-M_\mu M_\nu)+B(M^2)M_\mu M_\nu, \tag{14}$$

where $A(M^2)$ and $B(M^2)$ are given by

$$A(M^2)=-\frac{N_C}{3\pi}\left(1+\frac{m_c^2}{2M^2}\right)\left(1-\frac{m_c^2}{M^2}\right)^2\Theta(M^2-m_c^2),$$

$$B(M^2)=\frac{N_C}{2\pi}\frac{m_c^2}{M^2}\left(1-\frac{m_c^2}{M^2}\right)^2\Theta(M^2-m_c^2), \tag{15}$$

at tree level. As explained in [2], we set $m_c=1.0$ GeV to parametrize the higher-order QCD corrections to the current $b\to c\overline{c}s$.

We can now establish the connection between the semileptonic and the nonleptonic form factors. The differential decay width for the semileptonic decays is given by

$$\frac{d\Gamma}{dy} = \frac{G_F^2}{12\pi^3}|V_{cb}|^2 m_D^3 \sqrt{y^2-1}[(m_B-m_D)^2 E_S(y) + (m_B+m_D)^2 E_P(y) - M^2(E_V(y)+E_A(y))], \quad (16)$$

where $y=v\cdot v'$ and where the invariant mass M^2 is given by

$$M^2 = m_B^2 + m_D^2 - 2y m_B m_D. \quad (17)$$

The differential decay width for the right charm nonleptonic decays is then given by

$$\frac{d\Gamma}{dy} = C_1^2 N_C \frac{G_F^2}{12\pi^3}|V_{cb}V_{ud}^*|^2 m_D^3 \sqrt{y^2-1}[(m_B-m_D)^2 E_S(y) + (m_B+m_D)^2 E_P(y) - M^2(E_V(y)+E_A(y))]$$
$$+ C_1^2 \frac{G_F^2}{4\pi^2}|V_{cb}V_{cs}^*|^2 m_D^3 \sqrt{y^2-1}[(B(M^2)-A(M^2))((m_B-m_D)^2 E_S(y) + (m_B+m_D)^2 E_P(y))$$
$$+ A(M^2)M^2(E_V(y)+E_A(y))], \quad (18)$$

where $A(M^2)$ and $B(M^2)$ are given in Eq. (15). We see that the right charm semileptonic and nonleptonic decay widths are given in terms of the same form factors

$$4m_B m_D E_S(v\cdot v') = \sum_X \langle B(v)|[\overline{b}_v c_{v'}]|\overline{D}(v')X\rangle \times \langle \overline{D}(v')X|[\overline{c}_{v'} b_v]|B(v)\rangle,$$

$$-4m_B m_D E_P(v\cdot v') = \sum_X \langle B(v)|[\overline{b}_v \gamma_5 c_{v'}]|\overline{D}(v')X\rangle \times \langle \overline{D}(v')X|[\overline{c}_{v'} \gamma_5 b_v]|B(v)\rangle,$$

$$4m_B m_D E_V(v\cdot v') = \sum_X \langle B(v)|[\overline{b}_v \gamma^\mu c_{v'}]|\overline{D}(v')X\rangle \times \langle \overline{D}(v')X|[\overline{c}_{v'} \gamma_\mu b_v]|B(v)\rangle,$$

$$4m_B m_D E_A(v\cdot v') = \sum_X \langle B(v)|[\overline{b}_v \gamma^\mu \gamma_5 c_{v'}]|\overline{D}(v')X\rangle \times \langle \overline{D}(v')X|[\overline{c}_{v'} \gamma_\mu \gamma_5 b_v]|B(v)\rangle. \quad (19)$$

One important point should be stressed. This set (19) of nonperturbative form factors describes a transition from a B meson into a state with a D meson whatever the intermediate state might be. It has been shown in [1] that we can determine these matrix elements in the semileptonic case using constraints from the heavy quark symmetry (HQS) and a saturation assumption. These nonperturbative form factors were given in [1] for each single decay channel. So the nonleptonic right charm $B\to\overline{D}X$ decays can be deduced from the semileptonic ones. Note that we have neglected the renormalization-group improvement which had been considered in [1] since this effect is small. Therefore, we set $C_{11}=C_3=1$ and $C_{18}=0$ in the set of nonperturbative form factors given in [1].

After the connection between the nonleptonic and the semileptonic case has been established, we consider $B_s \to \overline{D}_s X$ and $B_s \to D_s X$ decays.

III. THE DECAYS $B_s \to \overline{D}_s X$ AND $B_s \to D_s X$

As mentioned previously the effective weak Hamiltonian is identical to the one of the $B\to\overline{D}X$ case, therefore, Eqs. (16) and (18) do also describe the right charm decay of a B_s meson into a $\overline{D}_s$ meson if one replaces m_B by m_{B_s} and m_D by m_{D_s}. We have a new set of nonperturbative form factors:

$$4m_{B_s} m_{D_s} E_S(v\cdot v') = \sum_X \langle B_s(v)|[\overline{b}_v c_{v'}]|\overline{D}_s(v')X\rangle \times \langle \overline{D}_s(v')X|[\overline{c}_{v'} b_v]|B_s(v)\rangle,$$

$$-4m_{B_s} m_{D_s} E_P(v\cdot v') = \sum_X \langle B_s(v)|[\overline{b}_v \gamma_5 c_{v'}]|\overline{D}_s(v')X\rangle \times \langle \overline{D}_s(v')X|[\overline{c}_{v'} \gamma_5 b_v]|B_s(v)\rangle,$$

$$4m_{B_s} m_{D_s} E_V(v\cdot v') = \sum_X \langle B_s(v)|[\overline{b}_v \gamma^\mu c_{v'}]|\overline{D}_s(v')X\rangle \times \langle \overline{D}_s(v')X|[\overline{c}_{v'} \gamma_\mu b_v]|B_s(v)\rangle,$$

$$4m_{B_s} m_{D_s} E_A(v\cdot v') = \sum_X \langle B_s(v)|[\overline{b}_v \gamma^\mu \gamma_5 c_{v'}]|\overline{D}_s(v')X\rangle \times \langle \overline{D}_s(v')X|[\overline{c}_{v'} \gamma_\mu \gamma_5 b_v]|B_s(v)\rangle. \quad (20)$$

Once again we can find a parametrization for these nonperturbative form factors using the semileptonic decays. We consider the s quark as being massless and we can, therefore, use the very same heavy quark symmetry relations as in the case $B\to\bar{D}X$. As it has been argued in [1], the HQS implies that at $v\cdot v'=1$ the inclusive rate is saturated by the exclusive decays into the lowest lying spin symmetry doublet $\bar{D}_s$ and $\bar{D}_s^*$. The $\bar{D}_s^*$ subsequently decays into $\bar{D}_s$ mesons and thus at $v\cdot v'=1$ the sum of the exclusive rates for $B_s\to\bar{D}_s l^+\nu$ and $B_s\to\bar{D}_s^* l^+\nu$ is equal to the one-particle inclusive semileptonic rate $B_s\to\bar{D}_s l^+\nu X$. Making use of this assumption and of the spin projection matrices for the heavy B_s and $\bar{D}_s^{(*)}$ mesons, we obtain

$$
\begin{aligned}
E_i(v\cdot v')=&\frac{1}{16}|\mathrm{Tr}\{\gamma_5(1+\not v)\Gamma_i(1+\not v')\gamma_5\}|^2|\xi(y)|^2\\
&+\frac{1}{16}\sum_{Pol}|\mathrm{Tr}\{\gamma_5(1+\not v)\Gamma_i(1+\not v')\not\epsilon\}|^2\\
&\times|\xi(y)|^2\mathrm{Br}(\bar{D}_s^*\to\bar{D}_sX),
\end{aligned}
\tag{21}
$$

where i stands for S, P, V or A, the sum is over the polarization of the D^* meson and $\xi(y)=1-0.84(y-1)$ is the Isgur-Wise function measured by CLEO [7]. The branching ratio $\mathrm{Br}(\bar{D}_s^*\to\bar{D}_sX)$ is the new input and since a D_s^{*-} always decays into a D_s^-, we have $\mathrm{Br}(\bar{D}_s^*\to\bar{D}_sX)=100\%$. We then obtain

$$
\begin{aligned}
E_S^{B_s^0D_s^-}(y)&=\frac{1}{4}(y+1)^2|\xi(y)|^2,\\
E_P^{B_s^0D_s^-}(y)&=\frac{1}{4}(y^2-1)|\xi(y)|^2,\\
E_V^{B_s^0D_s^-}(y)&=\frac{1}{2}(y+1)(2-y)|\xi(y)|^2,\\
E_A^{B_s^0D_s^-}(y)&=-\frac{1}{2}(y+2)(y+1)|\xi(y)|^2.
\end{aligned}
\tag{22}
$$

The nonleptonic decays $B_s\to\bar{D}_sX$ can be calculated using these nonperturbative form factors. It is clear that this saturation assumption is a crude approximation, but it is well motivated by the heavy quark symmetry at $y=1$ and the available phase space is not very large, so this has to be treated as a theoretical uncertainty due to nonperturbative physics. The results obtained for the semileptonic decays rates in $B\to\bar{D}Xl\nu$ [1] give us some confidence in our method.

We now consider the wrong charm decays of a B_s meson. They are induced by the quark transition $\bar{b}\to c$. The wrong charm $B_s^0\to D_s^{*+}X$ decay width can be estimated using the method described in [2], which corresponds to a rescaling of the parton calculation. In the leading order of the $1/N_C$ and of the $1/m_{B_s}$ expansions, the differential decay width reads

$$
\begin{aligned}
\frac{d\Gamma}{dy}=&\frac{3G_F^2C_1^2}{2\pi^3M^2}\sqrt{y^2-1}\,m_{D_s}^3|V_{cb}V_{cs}^*|^2y(M^2-m_{D_s}^2)^2\\
&\times\Theta(M^2-m_c^2)F,
\end{aligned}
\tag{23}
$$

where F is a channel-dependent nonperturbative form factor. We have

$$
F^{B_s^0D_s^+}=f(1+3\Gamma(D_s^*\to D_sX'))=4f,
\tag{24}
$$

where X' is a pion or a photon and f is the constant defined in [2]; we had $f=0.121$. Note that the wrong charm decay is being modeled and we have restricted ourselves to the so-called model 2 of [2] since this model seems to yield better results than model 1.

TABLE I. Comparison of our results with data. To get branching ratios, we used $\tau_{B_s^0}=1.55$ ps.

Mode	Br (theory)	Br (data from [8])
$B_s^0\to D_s^-X$	64.9%	$(92\pm33)\%$
$B_s^0\to D_s^+X$	3.3%	
$B_s^0\to D_s^-l^+\nu X$	9.1%	$(8.1\pm2.5)\%$
$B_s^0\to D_s^-\tau^+\nu_\tau X$	2.7%	
$B_s^0\to D_s^{*-}X$	49.6%	
$B_s^0\to D_s^{*+}X$	2.5%	
$B_s^0\to D_s^{*-}l^+\nu X$	7%	
$B_s^0\to D_s^{*-}\tau^+\nu_\tau X$	2%	

IV. DISCUSSION OF THE RESULTS

In Table I, we compare our predictions with the experimental data found in [8]. In the semileptonic case the method yields results which agree with the data. Note that we have considered the τ lepton as being massive. On the other hand, it is not clear if the nonleptonic decays are problematic; our results are in the experimental error range though at the inferior limit. One should keep in mind that we had estimated in [2] that corrections to our calculation could be fairly large and in the worst case up to 30%. It would be interesting to measure the rate $\Gamma(B_s\to\bar{D}_s^{*-}X)$ to test the agreement between theory and experiment in this channel. Remember that for the decays $B\to\bar{D}/DX$ described in [2], theory and experiment looked to be in agreement for the $B\to\bar{D}^*/D^*X$ decays and in disagreement for $B\to\bar{D}/DX$ decays although this could be accidental, for a discussion of this problem see [2].

Data are sparse on one-particle inclusive B_s decays; especially no spectra are available. It would be instructive to compare the spectra to check if the same discrepancy appears as in [2], where the spectra for the $B\to\bar{D}^*/D^*X$ meson decays seemed to be described correctly. On the other hand, the spectra for the decays of a $B\to\bar{D}/DX$ were not compatible with the experimental data, especially at the nonrecoil point where the method should work at its best, this effect being therefore very difficult to understand. Although the extension of the method developed for one-particle inclusive B decays to B_s decays is trivial, the results we have obtained are interesting especially in the perspective of B factories. These results could also be used to study mixing induced one-particle inclusive CP asymmetries in the B_s system [5], and this allows us to determine the weak angle γ, which is known to be very difficult.

If the problems encountered in the one-particle inclusive B decays [2] were not present in B_s decays, one could constrain the kind of diagrammatic topologies contributing to the one-particle inclusive B decays. In B decays as well as in B_s decays we have assumed that the dominant diagrammatical topology contributing to the right charm decay rates is spectator like. This study of B_s decays once confronted to more precise experimental results could allow one to test the influence of the light spectator quark.

V. CONCLUSIONS

We have clarified the link between the nonperturbative form factors of the semileptonic and nonleptonic $B \rightarrow \overline{D}X$. We have applied a method described in [1] and [2] to semileptonic and nonleptonic $B_s \rightarrow \overline{D}_s X$ and $B_s \rightarrow D_s X$ decays. This can be done easily by modifying the saturation assumption. It is too early to see if the same problems which were encountered in [2] also appear in our case, the reason being the lack of experimental data. Our results are compatible with current experimental knowledge.

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