CHARMED DECAYS OF THE B-MESON
IN THE QUARK MODEL

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Abstract

Exclusive and inclusive, semileptonic and non-leptonic, charmed decays of the B-meson are investigated in the context of a phenomenological quark model. Bound-state effects are taken care of by adopting a single (model-dependent) non-perturbative wave function, describing the motion of the light spectator quark in the $B$-meson. A nice reproduction of both exclusive and inclusive semileptonic data is obtained. Our predictions for the electron spectrum are presented and compared with those of the Isgur-Scora-Grinstein-Wise quark model. Finally, our approach is applied to the calculation of inclusive non-leptonic widths, obtaining a remarkable agreement with experimental findings.

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1 INTRODUCTION

Weak decays of hadrons containing a heavy quark could provide unique information on the fundamental parameters of the Standard Model and, at the same time, could serve as a probe of our understanding of the non-perturbative strong interaction phenomenology. From the theoretical point of view, the Heavy Quark Effective Theory (HQET) \[1\] is widely recognized as a very powerful tool for investigating decay modes of heavy flavours and, recently \[2\], a model-independent framework has been developed to treat non-perturbative QCD effects in inclusive decays. The latter approach relies on the formalism of HQET and on the use of the operator product expansion (OPE) in the physical region of time-like momenta. Thus, the hypothesis of quark-hadron duality, in its global form for semileptonic (SL) decays and in its local form for non-leptonic (NL) processes, has to be invoked \[3\]. The concept of quark-hadron duality, though it has not yet been derived from first principles, is essential in QCD phenomenology and corresponds to the assumption that the sum over many hadronic final channels eliminates bound-state effects related to the specific structure of each individual final hadron. The validity of the global duality has been tested in inclusive hadronic \(\tau\) decays \[4\], whereas the possibility of a failure of the local duality in inclusive NL processes has been raised recently in \[5\]. Therefore, the use of phenomenological quark models for the description of the hadron structure could be still of interest and, in this respect, it is well known that the constituent quark model is remarkably successful in describing the hadron mass spectra. However, any model of hadrons must go beyond the mass spectroscopy and predict, e.g., decay processes.

2 OUTLINE OF THE APPROACH AND RESULTS

In this contribution the exclusive and inclusive, SL and NL, charmed decays of the B-meson are investigated within the phenomenological quark model of Refs. \[6, 7\], where all the non-perturbative QCD bound-state effects are mocked up by a (model-dependent) light-cone wave function \(\chi(x, \vec{p}_1)\), describing the internal motion of the light spectator-quark inside the \(B\)-meson (with \(x\) and \(\vec{p}_1\) being the internal light-cone variables). The model dependence is illustrated adopting different \(B\)-meson wave functions, namely the phenomenological one of Ref. \[6\] and the two light-cone wave functions of Ref. \[7\], constructed from a relativized \[8\] and a non-relativistic \[9\] constituent quark model. In what follows, we will refer to these wave functions as cases A, B and C, respectively.

As for the exclusive \(B \to D\ell\nu\) and \(B \to D^*\ell\nu\) channels, the heavy quark limit of the relevant transition form factors is assumed and, therefore, the differential decay rates can be given only in terms of the Isgur-Wise (IW) function \[10\]. The latter has been explicitly calculated in case of the wave functions A, B and C in Refs. \[6, 11\] and \[7\], respectively. The results are reported in Fig. \[1\] and compared with the experimental data of Refs. \[12, 13, 14\]. It can clearly be seen that in the accessible recoil range our (model-dependent) predictions nicely reproduce exclusive SL experimental data. It is worth noting that the calculated slope \(\rho^2\) of the IW form factor turns out to be \(\sim 1\) for all the three wave functions, i.e. \(\sim 30\%\) higher than the prediction of the ISGW quark model \[15\] \((\rho^2_{ISGW} \sim 0.74)\).
Figure 1: The \( IW \) form factor \( \xi(\eta) \), times \(|V_{bc}|\), as a function of the velocity recoil \( \eta \). The open dots, full dots and squares correspond to the experimental data of Refs. [12], [13] and [14], respectively. The dotted, dashed and solid lines are our results obtained assuming \(|V_{bc}| = 0.0390 \) [6,7] and adopting the wave functions \( A \), \( B \) and \( C \), respectively (see text). Taken from Ref. [7].

As for the inclusive \( SL \) width, our approach, fully described in Refs. [6,7], is essentially inspired to the deep inelastic scattering approach [14], which pictures the heavy-meson decay as the decay of its partons. Our basic approximations for the calculation of the relevant weak hadronic tensor are the replacement of: i) the matrix element \( \langle n|J^{(h)}_\mu|B \rangle \) of the weak hadron current \( J^{(h)}_\mu \) between the B-meson state and the final multi-hadron state \( |n \rangle \) with the matrix element \( \langle c|J^{(q)}_\mu|b \rangle \) of the elementary \( b \to cW^- \) weak transition times the non-perturbative \( B \)-meson wave function \( \chi(x, \vec{p}_\perp) \); ii) the multi-hadron phase space \( d\tau_n \) with the two-body phase space \( d\tau_2(p_c, p_{sp}) \), where \( p_c \) and \( p_{sp} \) are the final \( c \)-quark and spectator quark momenta. Our results for various \( SL \) branching ratios are collected in Table [4], while the electron spectrum for the inclusive \( B \to X_c e\nu_e \) process is shown in Fig. [2] and compared with the predictions of the convolution approach of Ref. [19], based on a partial resummation of the \( OPE \) in the end-point region. It can clearly be seen that our predictions are in nice agreement with the experimental \( SL \) branching ratios and, at the same time, our calculated electron spectrum is consistent with the partially resummed \( OPE \) result.
Figure 2: The electron spectrum $\frac{1}{\Gamma_B} \frac{d\Gamma}{dE_e}$ as a function of the electron energy $E_e$ for the inclusive $B \to X_c e \nu_e$ decays. The dot-dashed line is the result obtained within the convolution approach of Ref. [19]. The meaning of the dotted, dashed and solid lines is the same as in Figure 1.

From Table 1 it can also be seen that our results for the contribution of the ”resonant” $B \to D \ell \nu_\ell$ and $B \to D^* \ell \nu_\ell$ channels to the total $SL$ branching ratio remarkably differ from the predictions of the ISGW quark model [15]. At variance with this model (and in accord with the experimental data), we find that $\sim 20\%$ and $\sim 70\%$ of the total $SL$ rate is due to the exclusive $D$ and $D + D^*$ decay modes, respectively, leaving a remarkable fraction ($\sim 30\%$) of the strength to other final states. Moreover, in Fig. 3 our results for the electron spectra are compared with the corresponding ISGW prediction [15]. It can be seen that, with respect to the results of our quark model, the ISGW model predicts both a larger strength in the resonant $D$ and $D^*$ channels and a lower strength in the total inclusive spectrum.

The results so far presented clearly illustrate that our quark model is successful in describing bound-state effects both in exclusive and inclusive $SL$ charmed decays. Therefore, we have applied our approach to the calculation of the inclusive widths of $NL$ charmed decays (see Refs. [6, 7]). For these processes our basic assumption is to incorporate all the long-range $QCD$ effects due to soft gluons into our non-perturbative wave function of the initial
Table 1: Branching ratios for semi-leptonic charmed decays of the $B$-meson. Cases $A$, $B$ and $C$ are described in the text. Equal charged and neutral $B$-meson production rates are assumed for the experimental data.

| Decay mode          | Case A | Case B | Case C | Exp. data       |
|---------------------|--------|--------|--------|-----------------|
| $\mathcal{B}(X_c \ell \nu_\ell)$ | 10.06  | 11.59  | 12.32  | 10.77 ± 0.43 [17] |
| $\mathcal{B}(X_c \tau \nu_\tau)$ | 2.26   | 2.46   | 2.56   | 2.60 ± 0.32 [17] |
| $\mathcal{B}(D^0 e\nu_e)$ | 1.83   | 2.07   | 1.69   | 1.75 ± 0.43 [18] |
| $\mathcal{B}(D^* e\nu_e)$ | 5.54   | 5.98   | 5.26   | 4.93 ± 0.42 [18] |

Adapted from Ref. [7].

$B$-meson and the final $D$ or $D^*$ mesons. Only the corrections due to hard-gluon exchange, yielding the effective weak Lagrangian of Ref. [20], are taken into account. Some of our results are collected in Table 2 and compared with experimental data. It can be seen that a good agreement (within 2$\sigma$) is achieved and, in particular, a non-negligible fraction of decays into baryon-antibaryon pairs is found. Note the good agreement of our predicted charm counting with recent experimental findings. Before closing, we want to point out that: i) the sum of all the calculated branching ratios turns out to be very close to 1 (see [7]); ii) radiative QCD corrections have been so far neglected; their net effect is expected to be of the same order of the uncertainties related to the model dependence of the $B$-meson wave function.

Table 2: Branching ratios for some non-leptonic charmed decays of the $B$-meson. Cases $A$, $B$ and $C$ are as in Table 1. Equal charged and neutral $B$-meson production rates are assumed for the experimental data.

| Decay mode          | Case A | Case B | Case C | Exp. data       |
|---------------------|--------|--------|--------|-----------------|
| $\mathcal{B}(D\pi)$ | 0.40   | 0.49   | 0.36   | 0.41 ± 0.03 [18] |
| $\mathcal{B}(D\rho)$ | 0.90   | 1.08   | 0.82   | 1.06 ± 0.11 [18] |
| $\mathcal{B}(D^*\pi)$ | 0.42   | 0.49   | 0.38   | 0.39 ± 0.04 [18] |
| $\mathcal{B}(D^*\rho)$ | 1.08   | 1.25   | 0.99   | 1.14 ± 0.17 [18] |
| $\mathcal{B}(\bar{D}D_s)$ | 1.55   | 1.75   | 1.43   | 1.10 ± 0.35 [21] |
| $\mathcal{B}(\bar{D}D^*_s)$ | 1.28   | 1.43   | 1.19   | 0.89 ± 0.31 [21] |
| $\mathcal{B}(\bar{D}^*D_s)$ | 1.09   | 1.20   | 1.02   | 1.12 ± 0.36 [21] |
| $\mathcal{B}(\bar{D}^*D^*_s)$ | 3.35   | 3.66   | 3.15   | 2.41 ± 0.74 [21] |
| $\mathcal{B}(\text{charmed baryons})$ | 8.24   | 5.15   | 3.86   | 6.4 ± 1.1 [18] |
| charm counting       | 1.21   | 1.20   | 1.20   | 1.16 ± 0.05 [17] |

1.23 ± 0.07 [22]

Adapted from Ref. [7].
Figure 3: The electron spectrum $\frac{1}{\Gamma_B} \frac{d\Gamma}{dE_e}$ as a function of the electron energy $E_e$ for the "resonant" $B \to D e\nu_e$ (dotted lines) and $B \to D^* e\nu_e$ (dashed lines) channels, as well as for the total inclusive $B \to X_c e\nu_e$ decay (solid lines). Thick lines correspond to the results obtained in our case $B$, whereas thin lines are the predictions of the ISGW model [15].

3 CONCLUSIONS

A phenomenological quark model, which takes into account non-perturbative QCD bound-state effects, has been applied to the investigation of exclusive and inclusive, semileptonic and non-leptonic, charmed decays of the $B$-meson, obtaining a remarkable agreement with available experimental data.

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