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Recent Developments in the Theory of Heavy-Quark Decays*

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ABSTRACT

I report on recent developments in the heavy-quark effective theory and its application to B meson decays. The parameters of the effective theory, the spin-flavor symmetry limit, and the leading symmetry-breaking corrections to it are discussed. The results of a QCD sum rule analysis of the universal Isgur-Wise functions that appear at leading and subleading order in the $1/m_Q$ expansion are presented. I illustrate the phenomenological applications of this formalism by focusing on two specific examples: the determination of V_{cb} from the endpoint spectrum in semileptonic decays, and the study of spin-symmetry violating effects in ratios of form factors. I also briefly comment on nonleptonic decays.

1 INTRODUCTION

The theoretical description of hadronic processes involving the decay of a heavy quark has recently experienced great simplification due to the discovery of new symmetries of QCD in the limit where $m_Q \rightarrow \infty$ [1, 2]. The properties of a hadron containing the heavy quark then become independent of its mass and spin, and the complexity of the hadronic dynamics results from the strong interactions among the light degrees of freedom only. The so-called heavy-quark effective theory (HQET) provides an elegant framework to analyze such processes [3]. It allows a systematic expansion of decay amplitudes in powers of $1/m_Q$.

In the formal limit of infinite heavy-quark masses, the spin-flavor symmetries impose restrictive constraints on weak decay amplitudes. In the case of semileptonic transitions between two heavy pseudoscalar or vector mesons, for instance, the large set of hadronic form factors reduces to a single universal function, the so-called Isgur-Wise form factor $\xi(v \cdot v')$. This function only depends on the change of velocities that the heavy mesons undergo during the transition. It is normalized at zero recoil ($v = v'$). This observation offers the exciting possibility of being able to extract in a model-independent way the weak mixing parameter V_{cb} from the measurement of semileptonic decays of beauty mesons or baryons,

without limitations arising from the ignorance of long-distance dynamics.

The heavy-quark symmetries greatly simplify the phenomenology of semileptonic weak decays in the limit where the heavy-quark masses can be considered very large compared to other hadronic scales in the process. But clearly, a careful analysis of symmetry-breaking corrections is essential for any phenomenological application. Already at leading order in the heavy-quark expansion the spin-flavor symmetries are violated by hard-gluon exchange. The corresponding corrections are of perturbative nature and are known very accurately to next-to-leading order in renormalization-group improved perturbation theory [4, 5, 6]. At order $1/m_Q$, on the other hand, one is forced to introduce a larger set of universal form factors, which are nonperturbative hadronic quantities such as the Isgur-Wise function itself [7, 8]. These functions characterize the properties of the light degrees of freedom in the background of the static color source provided by the heavy quark. Their understanding is at the heart of nonperturbative QCD. In this talk I review recent progress in this direction. I discuss the parameters of HQET, the leading QCD and $1/m_Q$ corrections to the infinite quark-mass limit, and some specific applications of the effective theory to semileptonic and nonleptonic B decays.

2 PARAMETERS OF HQET

The construction of HQET is based on the observation that, in the limit $m_Q \gg \Lambda_{QCD}$, the velocity v_μ of a heavy quark is conserved with respect to soft

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processes. It is then possible to remove the mass-dependent piece of the momentum operator by a field redefinition. To this end, one introduces a field $h_Q(v, x)$, which annihilates a heavy quark Q with velocity v ($v^2 = 1, v_0 \geq 1$), by [3]

$$h_Q(v, x) = \frac{(1 + \not{v})}{2} \exp(im_Q v \cdot x) Q(x). \quad (1)$$

If P_μ is the total momentum of the heavy quark, the new field carries only the residual momentum $k_\mu = P_\mu - m_Q v_\mu$, which is of order Λ_{QCD} . In the limit $m_Q \rightarrow \infty$ the effective Lagrangian for the strong interactions of the heavy quark becomes

$$\mathcal{L}_{\text{eff}} = \bar{h}_Q i v \cdot D h_Q - \delta m_Q \bar{h}_Q h_Q, \quad (2)$$

where D_μ is the covariant derivative, and δm_Q denotes the residual mass of the heavy quark in the effective theory [9].

Note that there is some ambiguity associated with the construction of HQET, since the heavy-quark mass used in the definition of the field h_Q is not uniquely defined. In fact, for HQET to be consistent it is only necessary that δm_Q and k_μ be of order Λ_{QCD} , i.e., stay finite in the limit $m_Q \rightarrow \infty$. A redefinition of m_Q by a small amount Δ induces changes in these quantities. In particular, if $m_Q \rightarrow m_Q + \Delta$, then $\delta m_Q \rightarrow \delta m_Q - \Delta$. Hence there is a unique choice m_Q^* for the heavy-quark mass in the construction of the effective theory such that the residual mass vanishes, $\delta m_Q = 0$. This prescription provides a nonperturbative definition of the heavy-quark mass, which has been implicitly adopted in most previous analyses based on HQET. Yet it is important to notice that the mass m_Q^* is a non-trivial parameter of the theory. For instance, one can associate the difference $\bar{\Lambda}$ between this mass and the mass of a meson M (or baryon) containing the heavy quark with the energy carried by the light constituents. That $\bar{\Lambda}$ is in fact a parameter characterizing the properties of the light degrees of freedom becomes explicit in the relation

$$\bar{\Lambda} = m_M - m_Q^* = \frac{\langle 0 | \bar{q} (i v \cdot \overline{D}) \Gamma h_Q | M(v) \rangle}{\langle 0 | \bar{q} \Gamma h_Q | M(v) \rangle}, \quad (3)$$

which can be derived from the equations of motion of HQET [9]. Here Γ is an appropriate Dirac matrix such that the currents interpolate the heavy meson M .

The two parameters m_Q^* and $\bar{\Lambda}$ characterize the static properties of the heavy quark and of the light degrees of freedom. Their ratio determines the size

of power corrections to the infinite quark-mass limit. Assuming $\bar{\Lambda} \simeq 0.50$ GeV one expects $\bar{\Lambda}/2m_Q^* \simeq 5\%$ and $\bar{\Lambda}/2m_c^* \simeq 20\%$ for the leading power corrections relevant to processes involving B or D mesons, respectively. This estimate is confirmed by detailed computations (see below).

Because of the spin-flavor symmetry the non-trivial dynamical properties of a hadron containing the heavy quark are entirely related to its light constituents. Consider, for instance, a transition between two heavy mesons (pseudoscalar or vector), $M \rightarrow M'$, induced by a weak current. At leading order in the heavy-quark expansion the associated hadronic matrix element factorizes into a trivial kinematical part, which depends on the mass and spin-parity quantum numbers of the mesons, and a reduced matrix element, which describes the elastic transition of the light degrees of freedom. Introducing spin wave-functions by

$$\mathcal{M}(v) = \sqrt{m_M} \frac{(1 + \not{v})}{2} \begin{cases} -\gamma_5 & ; J^P = 0^- \\ \not{v} & ; J^P = 1^- \end{cases} \quad (4)$$

one finds

$$\langle M' | h_Q \Gamma h_Q | M \rangle = -\xi(w) \text{Tr} \{ \overline{\mathcal{M}}(v') \Gamma \mathcal{M}(v) \}, \quad (5)$$

where $w = v \cdot v'$, and $\xi(w)$ is the universal Isgur-Wise form factor [2, 4]. It measures the overlap of the wave functions of the light degrees of freedom in the two mesons moving at velocities v and v' . The conservation of the vector current implies that there is complete overlap if $v = v'$, such that at zero recoil $\xi(1) = 1$.

Let us now focus on semileptonic decays of B mesons. It is convenient to define a set of heavy-meson form factors $h_i(w)$ by

$$\begin{aligned} \langle D(v') | V_\mu | \bar{B}(v) \rangle \\ = \sqrt{m_B m_D} \left[h_+(w) (v + v')_\mu + h_-(w) (v - v')_\mu \right], \end{aligned}$$

$$\begin{aligned} \langle D^*(v') | V_\mu | \bar{B}(v) \rangle \\ = i \sqrt{m_B m_D} h_V(w) \epsilon_{\mu\nu\alpha\beta} \epsilon^{*\nu} v'^\alpha v^\beta, \end{aligned} \quad (6)$$

$$\begin{aligned} \langle D^*(v') | A_\mu | \bar{B}(v) \rangle \\ = \sqrt{m_B m_D} \left[h_{A_1}(w) (w + 1) \epsilon_\mu^* \right. \\ \left. - h_{A_2}(w) \epsilon^* \cdot v v_\mu - h_{A_3}(w) \epsilon^* \cdot v v'_\mu \right], \end{aligned}$$

where $V_\mu = \bar{c} \gamma_\mu b$ and $A_\mu = \bar{c} \gamma_\mu \gamma_5 b$, and ϵ_μ is the polarization vector of the D^* meson. In the infinite

quark-mass limit one finds from (5)

$$\begin{aligned} h_+(w) &= h_V(w) = h_{A_1}(w) = h_{A_3}(w) \simeq \xi(w), \\ h_-(w) &= h_{A_2}(w) = 0. \end{aligned} \quad (7)$$

These relations summarize the symmetry constraints imposed on the weak matrix elements.

The mass parameter $\bar{\Lambda}$ and the Isgur-Wise functions are fundamental hadronic quantities that appear at leading order of the heavy-quark expansion. They can only be computed using nonperturbative techniques such as lattice gauge theory or QCD sum rules. While no lattice results are available so far, QCD sum rules [10] have often been used successfully to compute hadron masses, decay constants, and form factors. This method has been recently applied to the analysis of form factors in HQET [11, 12, 13]. From the study of the correlator of two heavy-light currents in the effective theory one finds that [11]

$$\Lambda = 0.50 \pm 0.07 \text{ GeV}, \quad (8)$$

corresponding to heavy-quark masses $m_c^* \simeq 4.8$ GeV and $m_b^* \simeq 1.4$ GeV. The Isgur-Wise function is obtained from the analysis of a three-current-correlator. The result can be parameterized in terms of a pole-type function

$$\xi(w) \simeq \left(\frac{2}{w+1} \right)^{\beta(w)}; \quad \beta(w) = 2 + \frac{0.6}{w}. \quad (9)$$

It explicitly obeys the normalization condition $\xi(1) = 1$ and exhibits dipole behavior at large recoil.

3 SYMMETRY-BREAKING CORRECTIONS

From the fact that the mass of the charm quark is not particularly large compared to a hadronic scale such as $\bar{\Lambda}$ one expects substantial symmetry-breaking corrections to the relations (7). These have to be incorporated in any phenomenological analysis based on HQET if the effective theory is to be more reliable than a particular model for the hadronic form factors. The leading corrections come from hard-gluon exchange and from terms of order $1/m_Q^2$ in the heavy-quark expansion. I will discuss these corrections separately below. Fortunately, it turns out that at least at zero recoil they can be calculated in an almost model-independent way, such that reliable predictions beyond the infinite quark-mass limit are still possible.

Table 1: The universal form factors at leading and subleading order in HQET.

function	normalization	broken symmetries
$\xi(v \cdot v')$	$\xi(1) = 1$	no
$\xi_3(v \cdot v')$	no	spin, flavor
$\chi_1(v \cdot v')$	$\chi_1(1) = 0$	flavor
$\chi_2(v \cdot v')$	no	spin, flavor
$\chi_3(v \cdot v')$	$\chi_3(1) = 0$	spin, flavor

In order to make the heavy-quark symmetry limit and the leading symmetry-breaking corrections to it explicit, I write

$$h_i(w) = \left[\alpha_i + \beta_i(w) + \gamma_i(w) + \dots \right] \xi(w), \quad (10)$$

where $\alpha_+ = \alpha_V = \alpha_{A_1} = \alpha_{A_3} = 1$ and $\alpha_- = \alpha_{A_2} = 0$, the functions $\beta_i(w)$ are the short-distance perturbative corrections, and $\gamma_i(w)$ contain the $1/m_c^2$ and $1/m_b^2$ corrections. The ellipses represent higher-order terms.

3.1 QCD Corrections

The form factors receive perturbative corrections due to the coupling of hard gluons to the heavy quarks. The corresponding coefficients $\beta_i(w)$ in (10) are complicated functions of w , $\alpha_s(m_c^*)$, $\alpha_s(m_b^*)$, and the mass ratio m_c^*/m_b^* . Their calculation is, however, purely perturbative and can make use of the powerful methods of the renormalization group [4, 5, 6]. The coefficients $\beta_i(w)$ are known to next-to-leading logarithmic order and are tabulated in Refs. [6].

3.2 $1/m_Q^2$ Corrections

At subleading order in the heavy-quark expansion the currents no longer have the simple structure as in (5). Instead, there appear higher-dimensional operators such as

$$\frac{1}{2m_Q^2} \bar{h}_Q \Gamma i \not{D} h_Q, \quad (11)$$

whose hadronic matrix elements give rise to new universal form factors. In total, four additional functions are required to describe all $1/m_Q^2$ corrections to transitions between two heavy mesons [7, 14]. Their properties are collected in Table 1.

Table 2: Total symmetry-breaking corrections $\delta_{\xi}(w) = \beta_{\xi}(w) + \gamma_{\xi}(w)$ in %.

w	δ_+	δ_-	δ_V	δ_{A_1}	δ_{A_2}	δ_{A_3}
1.0	2.6	-9.5	31.0	-1.5	-34.1	-1.9
1.1	2.4	-9.5	29.6	-0.9	-31.7	-0.9
1.2	3.1	-9.4	29.2	0.6	-29.6	0.9
1.3	4.9	-9.5	29.8	2.8	-27.6	3.4
1.4	7.3	-9.6	31.1	5.7	-25.8	6.4
1.5	10.4	-9.7	33.2	9.0	-24.2	10.0

The conservation of the vector current implies that two of these functions vanish at zero recoil. As a consequence, the hadronic form factors $h_+(w)$ and $h_{A_1}(w)$ are protected against $1/m_Q^2$ corrections at $w = 1$. This is the content of Luke's theorem [7].

The subleading universal functions can again be calculated using QCD sum rules in the effective theory. One finds [13]

$$\begin{aligned}\xi_3(w) &\simeq \frac{1}{3} [\xi(w) - \kappa(w-1)], \\ \chi_1(w) &\simeq \frac{2}{3} \frac{w-1}{w+1} \left[\left(4w + \frac{7}{2}\right) \kappa - \xi(w) \right] + 18 \lambda_3(w), \\ \chi_2(w) &\simeq 0, \\ \chi_3(w) &\simeq \frac{\kappa}{8} [1 - \xi(w)].\end{aligned}\quad (12)$$

Nonperturbative effects are contained in the Isgur-Wise function and the parameter $\kappa \simeq 0.16$, which is proportional to the mixed quark-gluon condensate $\langle \bar{q} \sigma_{\mu\nu} G^{\mu\nu} q \rangle$. One does indeed find that the functions $\chi_1(w)$ and $\chi_3(w)$ vanish at $w = 1$. In addition, restricting to the diagrams usually included in a sum rule analysis one finds no contribution to the spin-symmetry violating form factor $\chi_2(w)$, and obtains the parameter-free prediction

$$\xi_3(1) = \frac{1}{3}.\quad (13)$$

Corrections to this relation are expected to be small.

In Table 2, I show the theoretical prediction for the sum of the symmetry-breaking corrections to the various heavy-meson form factors, based on the most recent calculation of QCD corrections [6] and the above sum rule results. The relations between the corrections $\gamma_{\xi}(w)$ and the subleading universal functions are given in Ref. [14].

4 PHENOMENOLOGICAL APPLICATIONS

The theoretical results summarized in Table 2 form a solid basis for a comprehensive analysis of semileptonic B decays to subleading order in HQET. Some specific applications, as well as the extension to non-leptonic decays, are discussed below. I do not address here the important issue of decay constants of heavy mesons. The reader interested in this subject is referred to Refs. [11, 12].

4.1 Measurement of V_{cb}

As a first application let me focus on the extraction of the quark-mixing parameter V_{cb} from the extrapolation of semileptonic B decay rates to zero recoil. This subject has been discussed in detail in Ref. [15]. In general, one finds that

$$\begin{aligned}\lim_{w \rightarrow 1} \frac{1}{[w^2 - 1]^{1/2}} \frac{d\Gamma(\bar{B} \rightarrow D^* \ell \bar{\nu})}{dw} &= \frac{G_F^2}{4\pi^3} |V_{cb}|^2 (m_B - m_D)^2 m_D^3 \eta^*, \\ \lim_{w \rightarrow 1} \frac{1}{[w^2 - 1]^{3/2}} \frac{d\Gamma(\bar{B} \rightarrow D \ell \bar{\nu})}{dw} &= \frac{G_F^2}{48\pi^3} |V_{cb}|^2 (m_B + m_D)^2 m_D^3 \eta^2,\end{aligned}\quad (14)$$

with $\eta^* = \eta = 1$ in the infinite quark-mass limit. Because of Luke's theorem the decay rate for $\bar{B} \rightarrow D^* \ell \bar{\nu}$ is protected against $1/m_Q^2$ corrections at zero recoil. Thus to subleading order in HQET the coefficient η^* deviates from unity only due to radiative corrections. Ignoring terms of order $1/m_Q^2$, one finds that $\eta^* = 1 + \delta_{\text{QCD}}^*$ with $\delta_{\text{QCD}}^* \simeq -0.01$ [6]. On the other hand, Luke's theorem does not apply for $\bar{B} \rightarrow D \ell \bar{\nu}$ decays because the decay rate is helicity-suppressed at zero recoil [14, 15]. In this case $\eta = 1 + \delta_{\text{QCD}} + \delta_{1/m_Q^2}$ with $\delta_{\text{QCD}} \simeq 0.05$ and

$$\delta_{1/m_Q^2} = \frac{\bar{\Lambda}}{2} \left(\frac{1}{m_c^2} + \frac{1}{m_s^2} \right) \left(\frac{m_B - m_D}{m_B + m_D} \right)^2 [1 - 2\xi_3(1)],\quad (15)$$

which gives $\delta_{1/m_Q^2} \simeq 0.02$. Note that the $1/m_Q^2$ corrections are suppressed by the Voloshin-Shifman factor $[(m_B - m_D)/(m_B + m_D)]^2 \simeq 0.23$ [1], and that the corrections to the sum rule prediction $\xi_3(1) = 1/3$ are expected to be small. Since the canonical size of $1/m_Q^2$ corrections is 1–5%, I thus conclude that the theoretical uncertainty in η is comparable to that in η^* . Hence one should extract V_{cb} from

both decay modes, using the theoretical numbers

$$\eta^* \simeq 0.99, \quad \eta \simeq 1.07, \quad (16)$$

which are expected to have an accuracy of better than 5%.

Until now such an analysis has only been performed for $\bar{B} \rightarrow D^* \ell \bar{\nu}$ [15]. Using the updated value for the total branching ratio as measured by CLEO, $\mathcal{B}(\bar{B} \rightarrow D^* \ell \bar{\nu}) = 4.4 \pm 0.5\%$ [16], I find

$$V_{cb} = 0.040 \pm 0.005 \quad (17)$$

for $\tau_B = 1.3$ ps.

4.2 Ratios of Form Factors

It has been emphasized in Ref. [13] that a measurement of spin-symmetry-breaking effects in ratios of the various form factors that describe $\bar{B} \rightarrow D^* \ell \bar{\nu}$ transitions would not only offer the possibility of a nontrivial test of HQET beyond the leading order, but also provide valuable information about non-perturbative QCD. In the limit where the lepton mass is neglected, two axial form factors, $A_1(q^2)$ and $A_2(q^2)$, and one vector form factor, $V(q^2)$, are observable in these decays. The ratios

$$R_1 = \left[1 - \frac{q^2}{(m_B + m_{D^*})^2} \right] \frac{V(q^2)}{A_1(q^2)}, \quad (18)$$

$$R_2 = \left[1 - \frac{q^2}{(m_B + m_{D^*})^2} \right] \frac{A_2(q^2)}{A_1(q^2)}$$

become equal to unity in the infinite quark-mass limit and are thus sensitive measures of symmetry-breaking effects.

To subleading order in HQET, I write

$$R_i = 1 + \varepsilon_i^{\text{QCD}} + \varepsilon_i^{1/m_Q^2}; \quad i = 1, 2. \quad (19)$$

The theoretical prediction for ε_i as a function of q^2 is shown in Table 3. I propose a measurement of these quantities as an ideal test of the heavy-quark expansion for $b \rightarrow c$ transitions. In particular, note that the large values of R_1 result from both large QCD and $1/m_Q^2$ corrections. The latter ones are to a large extent model-independent since the subleading universal functions only appear in the $1/m_b^2$ terms [13]. Thus the sizeable deviation of R_1 from the symmetry limit $R_1 = 1$ is an unambiguous prediction of HQET. A measurement of this ratio with an accuracy of 10% could provide valuable information about the size of higher-order corrections. The

Table 3: Theoretical predictions for the symmetry-breaking corrections ε_i in %.

q^2 [GeV ²]	$\varepsilon_1^{\text{QCD}}$	ε_1^{1/m_Q^2}	$\varepsilon_2^{\text{QCD}}$	ε_2^{1/m_Q^2}
10.69	12.0	19.1	0.5	-11.0
8.57	11.7	18.2	0.5	-10.3
6.45	11.3	17.5	0.5	-9.6
4.33	11.0	16.8	0.5	-8.9
2.21	10.7	16.2	0.5	-8.3
0.09	10.4	15.6	0.5	-7.7

ratio R_2 , on the other hand, receives only very small QCD corrections and is sensitive to the subleading form factors $\xi_3(w)$ and $\chi_3(w)$. It can be used to test the sum rule predictions (12). For the practical feasibility of such tests it seems welcome that the theoretical predictions for both ratios are almost independent of q^2 ($R_1 \simeq 1.3$ and $R_2 \simeq 0.9$), such that it suffices to measure the integrated ratios.

4.3 Nonleptonic Decays

As a final application, let me briefly comment on nonleptonic two-body decays of B mesons. In this case, the heavy-quark symmetries do not yield relations as restrictive as those for semileptonic transitions. One still has to rely on the factorization hypothesis, under which the complicated hadronic matrix elements of the weak Hamiltonian reduce to products of decay constants and matrix elements of current operators, which are of the same type as those encountered in semileptonic processes. It is at this stage that the heavy-quark symmetries can be advantageously incorporated, leading to essentially model-independent predictions for the factorized decay amplitudes. This provides for the first time a clean framework in which to test factorization. The procedure would be as follows: One extracts the Isgur-Wise function from data on semileptonic B decays and incorporates the leading symmetry-breaking corrections as discussed above. This determines the functions $h_i(w)$, which suffice to compute all matrix elements that appear in the factorized decay amplitudes for nonleptonic processes. Besides decay constants, these amplitudes contain two parameters, a_1 and a_2 , which are related to the Wilson coefficients of the effective Hamiltonian. They would be universal numbers if factorization were ex-

act. In cases where the relevant decay constants are known, a case-by-case determination of a_1 or a_2 provides a test of factorization. In other cases, one may rely on factorization to obtain estimates for yet unknown decay constants such as f_{D_s} . Both strategies have been pursued by various authors, and we refer the interested reader to the literature [17].

5 CONCLUSIONS

I have presented a short overview of recent developments in the theory of heavy-quark decays. The spin-flavor symmetries that QCD reveals for heavy quarks lead to relations among the hadronic form factors which describe semileptonic decays of heavy mesons or baryons. The heavy-quark effective theory provides a convenient framework for the analysis of such processes. It allows a separation of short- and long-distance phenomena in such a way that the nontrivial dynamical information is parameterized in terms of universal functions, which describe the properties of the light degrees of freedom in the background of the static color source provided by the heavy quark. These functions are fundamental, nonperturbative quantities of QCD. I have presented explicit expressions for them obtained from QCD sum rules. In the near future, similar results should be obtainable from lattice gauge theory.

If the leading symmetry-breaking corrections are taken into account, the heavy-quark effective theory forms a solid, almost model-independent basis for an analysis of many weak decay processes. I have discussed the determination of V_{cb} from the endpoint spectrum in semileptonic B decays, and the study of symmetry-breaking effects in ratios of form factors, which offers nontrivial tests of the heavy-quark expansion beyond leading order. I have also emphasized that the use of the spin-flavor symmetry may provide a cleaner basis for tests of factorization in nonleptonic two-body decays of B mesons.

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