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Note on the slope parameter of the baryonic $\Lambda_b \to \Lambda_c$ Isgur–Wise function

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Abstract

Using the framework of the Heavy Quark Effective Theory we have re-analyzed the Isgur–Wise function describing semi-leptonic $\Lambda_b \to \Lambda_c$ decays in the QCD sum rule approach. The slope parameter of the Isgur–Wise function is found to be $\rho^2 = 1.35 \pm 0.13$, which is consistent with an experimental measurement and a lattice calculation. To $\mathcal{O}(1/m_b, 1/m_c)$ of the heavy quark expansion the integrated Λ_b decay width is used to extract the CKM matrix element V_{cb} for which we obtain a value of $|V_{cb}| = 0.041 \pm 0.004 \pm 0.001$ in excellent agreement with the value of $|V_{cb}|$ determined from semileptonic $B \to D^*$ decays.

The study of $b \to c$ semileptonic weak decays has been the subject of considerable interest in recent years, as a source of information on V_{cb} and as a laboratory for understanding the strong interaction effects and developing nonperturbative QCD methods. A considerable amount of work has been carried out in the meson sector, in which the Heavy Quark Effective Theory (HQET) [1] was first developed. In the baryon sector a particular example is the semileptonic decay $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$. In view of the fact that a recent experiment from DELPHI [2] shows a discrepancy with the results of previous QCD sum rule calculations [3,4] an updated sum rule analysis for the baryonic $\Lambda_b \to \Lambda_c$ form factor is called for.

In the heavy quark limit, the hadronic matrix element of the $\Lambda_b \to \Lambda_c$ transition can be simply expressed in terms of a single Isgur–Wise (IW) function defined as follows [5–7],

$$\langle \Lambda_c(v') | \bar{c} \Gamma b | \Lambda_b(v) \rangle = \xi(\omega) \bar{u}_{\Lambda_c}(v') \Gamma u_{\Lambda_b}(v), \qquad (1)$$

where $\omega = v \cdot v'$ is the velocity transfer variable and Γ is an arbitrary gamma matrix. When the velocity of the heavy quark changes from v to v' due to the weak

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decay of the heavy quark, the light degrees of freedom undergo a corresponding transition due to their strong interactions with the heavy quark. The Isgur–Wise (IW) function $\xi(\omega)$ is a measure of the transition amplitude of the light degrees of freedom. The IW function $\xi(\omega)$ is normalized to 1 at the zero recoil point $\omega = 1$. This value is reduced by a few percent after taking into account radiative QCD correction effects [8,9].[1] To obtain a theoretical description of the whole IW function one must use nonperturbative methods which, at the current stage, are beset with large uncertainties. In the decay $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$, the physical region of ω lies in the range 1 to 1.43. Usually the IW function is expanded up to the first order in $(\omega - 1)$,

$$\xi(\omega) = 1 - \rho^2(\omega - 1) + \mathcal{O}\big((\omega - 1)^2\big). \qquad (2)$$

The slope parameter ρ^2 of the IW function at zero recoil has to be calculated using nonperturbative methods.

The QCD sum rule approach [11,12] has proven to be a reliable tool to deal with many problems in the realm of nonperturbative QCD. It has been used successfully to calculate the properties of various hadrons. For instance, besides the light mesons and baryons, heavy meson properties were systematically analyzed in the sum rule approach within the framework of HQET [8]. In the heavy baryon sector the masses of heavy baryons and the IW functions describing their weak transitions were calculated in Refs. [3,4,13,14] and [15–19], respectively. In Ref. [20], the calculation for the heavy baryons began with the full theory and the results of the calculation were expanded in terms of inverse powers of the heavy quark masses. In the HQET sum rule approach the baryonic $\Lambda_b \to \Lambda_c$ IW function was calculated in [3,4], and the slope parameter ρ^2 was fitted to lie in the range 0.5–0.8. However, such low slope values would predict exclusive $\Lambda_b \to \Lambda_c$ semileptonic decay rates dangerously close to the inclusive semileptonic rate [21,22]. A first measurement of the IW function of semileptonic $\Lambda_b \to \Lambda_c$ transitions has recently been reported by the DELPHI Collaboration [2]. The errors on this measurement are quite large. Using an exponential parametrization, they quote a value of $\rho^2 = 1.59 \pm 1.10(\text{stat})$. When the observed event rates were included in the fit they obtained $\rho^2 = 2.03 \pm 0.46(\text{stat})^{+0.72}_{-1.00}(\text{syst})$ [2]. Within the large error bars the experimental slope value is compatible with the HQET sum rule results of [3,4] although the experimental central values of [2] are considerably higher than the theoretical sum rule results.

Theoretically, the above-mentioned HQET sum rule results for the slope parameter $\rho^2 = 0.5$–0.8 appear to be rather small. Because the number of light quark transitions is larger in the heavy baryon case than in the heavy meson case one expects that the slope of the baryonic IW function is larger than that of the mesonic IW function. In fact, in the large N_c limit, ρ^2 will be infinitely large [23]. In the spectator quark model approach [6,7,24] one finds $\rho^2 = 2\rho^2_{\text{meson}} - 1/2$ which turns into an upper bound $\rho^2 \leqslant 2\rho^2_{\text{meson}} - 1/2$ when the interaction between the light quarks is turned on [25].[2]

Concerning the slope parameter of the mesonic IW function, one finds theoretical values of about 1 from sum rule calculations [8]. Experimental numbers for the mesonic slope parameter also scatter around 1 [26–28]. Using the spectator quark model estimate one thus expects baryonic values of the slope parameter ρ^2 in the vicinity of 1.5 or slightly below that number. The Skyrme model predicts $\rho^2 \simeq 1.3$ [29]. In the infinite momentum frame model one has $\rho^2 = 1.44$ [18] and in the relativistic three quark model one finds $\rho^2 = 1.35$ [19]. For the baryonic sum rule results, radiative corrections to ρ^2 and $1/m_Q$ corrections to the form factors are not expected to be large enough to solve the discrepancy between the large experimental central value for ρ in [2] and the small QCD sum rule results [3,4]. We therefore concentrate only on the leading order results in our analysis.

The purpose of this work is to present a new QCD sum rule analysis for the leading-order Isgur–Wise function describing the $\Lambda_b \to \Lambda_c$ transition. In particular, we concentrate on the sum rule prediction directly for the slope parameter ρ^2. To start with, we first

[1] At zero recoil the $\Lambda_b \to \Lambda_c$ weak transition matrix elements have no $1/m_Q$ corrections, and the $1/m_Q^2$ corrections are small [10].

[2] The large N_c result in the spectator quark model approach can be worked out to be $\rho^2 = (N_c - 1)(\rho^2_{\text{meson}} - 1/4)$. Since $\rho^2_{\text{meson}} \geqslant 1/2$ according to the sum rule of Bjorken, one then recovers the infinite slope result of [23] in the large N_c limit.