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## Exclusive and Inclusive Semileptonic $\Lambda_b$ -Decays

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### Abstract

In this talk we present theoretical evidence that the exclusive/inclusive ratio of semileptonic  $\Lambda_b$ -decays exceeds that of semileptonic B-decays, where the experimental exclusive/inclusive ratio amounts to about 66%. We start from the observation that the spectator quark model provides a lower bound on the leading order Isgur-Wise function of the  $\Lambda_b \rightarrow \Lambda_c$  transition in terms of the corresponding  $B \rightarrow D, D^*$  mesonic Isgur-Wise function. Using experimental data for the  $B \rightarrow D, D^*$  mesonic Isgur-Wise functions this bound is established. Applying a QCD sum rule estimate of the  $\Lambda_b \rightarrow \Lambda_c$  transition form factor which satisfy the spectator quark model bound we predict the exclusive/inclusive ratio of semileptonic  $\Lambda_b$  decay rates to lie in a range between 0.81 and 0.89. We also provide an upper bound on the baryonic Isgur-Wise function which is determined from the requirement that the exclusive rate should not exceed the inclusive rate. Our pre-Osaka results are discussed in the light of new recent preliminary experimental results on the pertinent mesonic and baryonic form factors presented at the Osaka ICHEP 2000 Conference.

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# Exclusive and Inclusive Semileptonic $\Lambda_b$ -Decays

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In this talk we present theoretical evidence that the exclusive/inclusive ratio of semileptonic  $\Lambda_b$ -decays exceeds that of semileptonic B-decays, where the experimental exclusive/inclusive ratio amounts to about 66%. We start from the observation that the spectator quark model provides a lower bound on the leading order Isgur-Wise function of the  $\Lambda_b \rightarrow \Lambda_c$  transition in terms of the corresponding  $B \rightarrow D, D^*$  mesonic Isgur-Wise function. Using experimental data for the  $B \rightarrow D, D^*$  mesonic Isgur-Wise functions this bound is established. Applying a QCD sum rule estimate of the  $\Lambda_b \rightarrow \Lambda_c$  transition form factor which satisfy the spectator quark model bound we predict the exclusive/inclusive ratio of semileptonic  $\Lambda_b$  decay rates to lie in a range between 0.81 and 0.89. We also provide an upper bound on the baryonic Isgur-Wise function which is determined from the requirement that the exclusive rate should not exceed the inclusive rate. Our pre-Osaka results are discussed in the light of new recent preliminary experimental results on the pertinent mesonic and baryonic form factors presented at the Osaka ICHEP 2000 Conference.

## 1. Introduction

In mesonic semileptonic  $b \rightarrow c$  transitions, the exclusive transitions to the ground state  $S$ -wave mesons  $B \rightarrow D, D^*$  make up approximately 66% of the total semileptonic  $B \rightarrow X_c$  rate [1]. In this talk we are concerned about expectations for the corresponding percentage figure in semileptonic bottom baryon decays, i.e. we are interested in the ratio of the semileptonic transition rates  $R_E = \Gamma_{\Lambda_b \rightarrow \Lambda_c} / \Gamma_{\Lambda_b \rightarrow X_c}$ . Unfortunately nothing is known experimentally about this ratio yet. Using some theoretical input and data on bottom meson decays we predict that the baryonic rate ratio  $R_E$ (baryon) lies in the range  $0.81 \div 0.92$  [2] and is therefore predicted to be larger than the corresponding mesonic rate ratio  $R_E$ (meson)  $\approx 66\%$ .

In fact this investigation was prompted by two questions on related rate ratios posted to us by experimentalists. G. Sciolia asked us about the

semileptonic rate ratio

$$R_A = \frac{\Gamma(\Lambda_b \rightarrow \Lambda_c X l \nu)}{\Gamma(\Lambda_b \rightarrow X_c l \nu)}, \quad (1)$$

while P. Roudeau wanted to know about theoretical expectations for the ratio

$$R_B = \frac{\Gamma(\Lambda_b \rightarrow X_c (non \Lambda_c) l \nu)}{\Gamma(\Lambda_b \rightarrow X_c l \nu)}. \quad (2)$$

It is very difficult to make reliable theoretical predictions for these two semi-inclusive and inclusive ratios. However, in as much as one has the constraint relation

$$R_E + R_A + R_B = 1, \quad (3)$$

and, in as much as all three ratios in (3) are positive definite quantities, a large number for  $R_E$  close to one, as predicted by us, would limit the ratios  $R_A$  and  $R_B$  to rather small values.

The size of the exclusive rate  $\Gamma_{\Lambda_b \rightarrow \Lambda_c}$  is tied to the shape of the Isgur-Wise form factor  $F_B(\omega)$  for the  $\Lambda_b \rightarrow \Lambda_c$  transition. Expanding  $F_B(\omega)$  about the zero recoil point  $\omega = 1$ , where  $F_B(\omega)$  is normalized to one, one writes

$$F_B(\omega) = F_B(1)[1 - \rho_B^2(\omega - 1) + c_B(\omega - 1)^2 + \dots]. \quad (4)$$

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The coefficients  $\rho_B^2$  and  $c_B$  are called the slope parameter and the convexity parameter, respectively. The slope parameter  $\rho_B^2$  is frequently used to characterize the fall-off behaviour of the Isgur-Wise function. We have to caution the reader, though, that it can be quite misleading to use the linear approximation over the whole range of  $\omega$  even if the physical range of  $(\omega - 1)$  in this process is quite small ( $0 \div 0.43$ ). For example, if one calculates the rate, the weight factor which multiplies  $F_B(\omega)^2$  in the rate formula is strongly weighted towards the end of the  $\omega$ -spectrum and one will thus get quite misleading results if one uses the linear approximation for the Isgur-Wise function. Besides, if  $\rho_B^2$  exceeds 2.31,  $F_B(\omega)$  would become negative in the physical region which is physically unacceptable.

There is a longstanding controversy about the size of the baryonic slope parameter  $\rho_B^2$ . A first preliminary experimental measurement of  $\rho_B^2$  was presented at the HEP'99 Tampere conference by the DELPHI Collaboration [3]. They obtained the rather large value of

$$\rho_B^2 = 3.4 \pm 1.3 \pm 0.7. \quad (5)$$

Theoretical models offer a wide range of predictions. Taking a representative set of eight different theoretical models the slope parameter varies in the range  $\rho_B^2 = 0.33 \div 2.35$  [4–11]. We emphasize that this list is not exhaustive. In this talk we present lower and upper bounds on the slope parameter which read [2]

$$0.36 \leq \rho_B^2 \leq 0.89 \pm 0.19. \quad (6)$$

These bounds exclude the model of [4] on the low side and the models [8–11] on the high side. Also the preliminary DELPHI result (5) can be seen to violate the upper bound.

## 2. Origin of bounds

The upper bound on  $\rho_B^2$  has its origin in a spectator quark model relation which relates the baryonic form factor to the square of the mesonic form factor. The relation reads [12]

$$F_B(\omega) = \frac{\omega + 1}{2} |F_M(\omega)|^2. \quad (7)$$

The spectator quark model form factor can be seen to provide a lower bound to the baryonic form factor. This then leads to an upper bound on the baryon slope parameter given by

$$\rho_B^2 \leq 2\rho_M^2 - \frac{1}{2}. \quad (8)$$

Using an average of the experimental  $B \rightarrow D, D^*$  mesonic slope parameters [13] one then arrives at the upper bound in (6).

The physical picture behind the spectator quark model relation is quite simple. In the heavy baryon case there are two light spectator quarks that need to be accelerated in the current transition compared to the one spectator quark in the heavy meson transition. Thus the baryonic form factor is determined in terms of the square of the mesonic form factor. The factor  $(\frac{\omega+1}{2})$  is a relativistic factor which insures the correct threshold behaviour of the baryonic form factor in the crossed  $e^+e^-$ -channel [12,14].

In [14] the relation between heavy meson and heavy baryon form factors was investigated in the context of a dynamical Bethe-Salpeter (BS) model. The above spectator quark model relation (7) in fact emerges when the interaction between the light quarks in the heavy baryon is switched off in the BS-interaction kernel. In the more realistic situation when the light quarks interact with each other, the heavy baryon form factor becomes flatter, i.e. the spectator quark model form factor may be used to bound the heavy baryon form factor from below. This in turn leads to the upper bound on the slope parameter in (8).

On the other hand, the origin of the lower bound on  $\rho_B^2$  in (6) derives from the requirement that the exclusive rate should not exceed the inclusive rate, i.e.  $\Gamma_{\Lambda_b \rightarrow \Lambda_c} \leq \Gamma_{\Lambda_b \rightarrow X_c}$  as explained in more detail in the next section.

## 3. Numerical values of bounds

We begin by deriving the lower bound on  $\rho_B^2$  in (6). As explained before the lower bound is obtained from the requirement that the exclusive rate  $\Gamma_{\Lambda_b \rightarrow \Lambda_c}$  should not exceed the totally inclusive rate  $\Gamma_{\Lambda_b \rightarrow X_c}$ .

The exclusive rate is calculated using the following input:

- HQET to  $O(1+1/m_Q)$  where the  $O(1/m_Q)$  contribution of the so-called nonlocal form factor  $\eta(\omega)$  is dropped. The contribution of  $\eta(\omega)$  was found to be negligibly small in two model calculations [5,9].
- The  $O(1/m_Q^2)$  corrections at zero recoil are fully accounted for [15]. These are extended to the whole  $\omega$ -range using a technical smoothness assumption involving the lowest partial wave in the  $\Lambda_b \rightarrow \Lambda_c$ -transition.
- We use a standard (convex) form of the leading Isgur-Wise function given by

$$F_B(\omega) = \frac{2}{\omega+1} \exp\left(-(2\rho_B^2-1)\frac{\omega-1}{\omega+1}\right). \quad (9)$$

which has the correct zero recoil normalization  $F_B(1) = 1$ , a slope  $\rho_B^2$  and a convexity of  $(-1 + 4\rho_B^2 + \rho_B^4)/8$ .

- $O(\alpha_s)$  corrections are included according to the approximate scheme introduced in [16].

The inclusive rate  $\Gamma_{\Lambda_b \rightarrow X_c}$  is calculated using the following input:

- HQET to  $O(1+1/m_Q^2)$  thus including the  $O(1+1/m_Q^2)$  kinetic energy correction
- Full  $O(\alpha_s)$  corrections using the results of [17].
- A pole mass of  $m_b = 4.8$  GeV from the sum rule calculation of [18]

Using these ingredients we have obtained  $\Gamma_{\Lambda_b \rightarrow X_c} = 6.50 \cdot 10^{10} s^{-1}$  for the inclusive rate.

To obtain the numerical value of the lower bound  $(\rho_B^2)_{\min} = 0.36$  we have adjusted the slope parameter  $\rho_B^2$  in the exponential standard form (9) such that saturation  $R_E = 1$  is reached. As concerns the upper bound we have used the average of the experimental values of the mesonic slope parameters in  $B \rightarrow D, D^*$  [1,13] which we calculate as  $\rho_M^2 = 0.70 \pm 0.10$ . This then leads to the upper bound  $\rho_B^2 = 0.89 \pm 0.19$  according to the spectator quark model bound Eq.(8).

#### 4. Results on the exclusive/inclusive ratio $R_E$

We are now in a position to give our results for the exclusive/inclusive ratio  $R_E$ . We begin by recording our prediction for the exclusive rate for which we obtain

$$\Gamma_{\Lambda_b \rightarrow \Lambda_c} = 5.52 \cdot 10^{10} s^{-1} \quad (10)$$

using  $V_{bc} = 0.038$ . The exclusive rate is calculated using a slope value of  $\rho_B^2 = 0.75$  which is the average of the two slope values 0.65 and 0.85 resulting from the QCD sum rule analysis of non-diagonal and diagonal sum rules, respectively [6]. This value is identical to the sum rule result of [5]. We consider the sum rule calculations to be the most reliable at present. Note that the sum rule results lie within the bounds given by Eq.(6).

When calculating the exclusive/inclusive ratio we allow for a variation of the slope parameter between these two values of 0.65 and 0.85. Similarly we allow for a variation of the inclusive rate by using the results of either [18] or [19]. We thus obtain

$$R_E = 0.81 \div 0.92. \quad (11)$$

Note that the  $V_{bc}$ -dependence drops out in this ratio. Our conclusion is that the exclusive/inclusive ratio of semileptonic  $\Lambda_b$ -decays is considerably higher than in the corresponding bottom meson case.

#### 5. Summary

Let us summarize our findings. Our main predictions are the following:

- The slope parameter in baryonic  $\Lambda_b \rightarrow \Lambda_c$  transitions lies in the range

$$0.36 \leq \rho_B^2 \leq 0.89 \pm 0.19. \quad (12)$$

- The exclusive rate (using the central value of a QCD sum rule prediction  $\rho_B^2 = 0.75$  and  $V_{bc} = 0.038$ ) is

$$\Gamma_{\Lambda_b \rightarrow \Lambda_c} = 5.52 \cdot 10^{10} s^{-1} \quad (13)$$

which corresponds to a branching ratio of  $BR(\Lambda_b \rightarrow \Lambda_c l \nu) = 6.8\%$ . Considering the fact that experimentally one has a semi-exclusive branching ratio of  $BR(\Lambda_b \rightarrow \Lambda_c X l \nu) = (9.8_{-3.8}^{+3.1})\%$  [1] this does not leave much room for the inclusive “X”.

- The exclusive/inclusive semileptonic rate ratio (using  $\rho_B^2 = 0.65 \div 0.85$  from QCD sum rules, and [18] and [19] for  $\Gamma_{incl.}$ ) is predicted to be

$$R_E(\text{baryon}) = 0.81 \div 0.92. \quad (14)$$

$R_E(\text{baryon})$  is thus predicted to be larger than  $R_E(\text{meson}) \approx 66\%$ .

Since the time of this talk two new preliminary experimental results have appeared that are relevant to the results presented in this talk. The DELPHI Coll. has come out with new preliminary results on the slope of the baryonic Isgur-Wise function [20]. They now obtain slope values of  $\rho_B^2 = 1.65 \pm 1.3 \pm 0.6$  or, when they include the observed event rate in the fit,  $\rho_B^2 = 1.55 \pm 0.60 \pm 0.55$ . These new slope values are considerably smaller than their previous value (5). and are now clearly compatible with the bound (6) even if the central value is still somewhat high. The results of this new analysis were also presented at this meeting by T. Moa [21].

Furthermore, the CLEO Coll. has presented preliminary results of a new analysis of the slope parameter in mesonic  $B \rightarrow D^*$ -transitions based on a much larger data sample than the one that was used in the analysis of [13]. They now obtain  $\rho_M^2 = 1.67 \pm 0.11$  [22]. Using this new preliminary value on the mesonic slope parameter would move the upper bound on the baryonic slope parameter to  $(\rho_B^2)_{\max} = 2.84 \pm 0.22$ . This new upper bound is much less stringent than the upper bound  $(\rho_B^2)_{\max} = 0.89 \pm 0.19$  derived in [2] from previous CLEO data. The new upper bound would easily accommodate all theoretical models mentioned in Sec.I (except for [4] which violates the lower bound) as well as the old and new measurements of the DELPHI Coll. [3,20]. It will be interesting to see whether the new large mesonic

slope value measured by the CLEO Coll. is confirmed by measurements of BABAR and BELLE which hopefully will become available soon.

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