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Exclusive $c \to s, d$ semileptonic decays of spin-1/2 and spin-3/2 cb baryons

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Abstract We present results for exclusive semileptonic decay widths of ground state spin-1/2 and spin-3/2 cb baryons corresponding to a $c \to s, d$ transition at the quark level. The relevance of hyperfine mixing in spin-1/2 cb baryons is shown. Our form factors are compatible with heavy quark spin symmetry constraints obtained in the infinite heavy quark mass limit.

Keywords Doubly heavy cb baryon decay · heavy quark spin symmetry

1 Introduction

This contribution summarizes the work of Ref. [1]. There a systematic study of exclusive semileptonic decay widths of ground state spin-1/2 and spin-3/2 cb baryons ,driven by a $c \to s, d$ transition at the quark level, was done. Previous works [2; 3; 4] were limited to just a few decay channels.

The baryons considered in this work are summarized in Table 1. The quark masses and wave functions have been calculated with the AL1 potential of Ref. [5], using the variational procedure described in [6]. In that table the double heavy baryon states have been classified according to the total spin S of the heavy quark subsystem. This is based in heavy quark spin symmetry (HQSS) that tell us that for very large heavy quark masses one can select the heavy quark subsystem to have a well defined total spin. However, and because of the finite value of the heavy quark masses, one has that for spin-1/2 cb baryons, the hyperfine interaction between the light quark and any of the heavy quarks can admix both $S = 0$ and $S = 1$ components into their wave function. The actual spin-1/2 physical states are admixtures of the states Ξ_{cb} and Ξ'_{cb} (Ω_{cb} and Ω'_{cb}) given in Table 1. In Ref. [8] we study this mixing finding the physical states and masses to be

$$\begin{aligned}
\Xi^{(1)}_{cb} &= 0.431\Xi_{cb} - 0.902\Xi'_{cb}, \quad M_{\Xi^{(1)}_{cb}} = 6967\,\mathrm{MeV} \;\; ; \;\; \Xi^{(2)}_{cb} = 0.902\Xi_{cb} + 0.431\Xi'_{cb}, \quad M_{\Xi^{(2)}_{cb}} = 6919\,\mathrm{MeV} \\
\Omega^{(1)}_{cb} &= 0.437\Omega_{cb} - 0.899\Omega'_{cb}, \quad M_{\Omega^{(1)}_{cb}} = 7046\,\mathrm{MeV} \;\; ; \;\; \Omega^{(2)}_{cb} = 0.899\Omega_{cb} + 0.437\Omega'_{cb}, \quad M_{\Omega^{(2)}_{cb}} = 7005\,\mathrm{MeV}
\end{aligned} \tag{1}$$

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Table 1 Quantum numbers of baryons involved in this study. For the cb baryons, states with a well defined spin for the heavy subsystem are shown. J^π and I are the spin-parity and isospin of the baryon, while S^π is the spin-parity of the two heavy or the two light quark subsystem. n denotes a u or d quark. Experimental masses are isospin averaged over the values reported by the Particle Data Group [7].

Baryon	J^P	I	S^π	Quark content	Mass [MeV]	
					Quark model	Experiment
Ξ_{cb}	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	cbn	6928	–
Ξ'_{cb}	$\frac{1}{2}^+$	$\frac{1}{2}$	0^+	cbn	6958	–
Ξ^*_{cb}	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	cbn	6996	–
Ω_{cb}	$\frac{1}{2}^+$	0	1^+	cbs	7013	–
Ω'_{cb}	$\frac{1}{2}^+$	0	0^+	cbs	7038	–
Ω^*_{cb}	$\frac{3}{2}^+$	0	1^+	cbs	7075	–
Λ_b	$\frac{1}{2}^+$	0	0^+	udb	5643	5620.2 ± 1.6
Σ_b	$\frac{1}{2}^+$	1	1^+	nnb	5851	5811.5 ± 2.4
Σ^*_b	$\frac{3}{2}^+$	1	1^+	nnb	5882	5832.7 ± 3.1
Ξ_b	$\frac{1}{2}^+$	$\frac{1}{2}$	0^+	nsb	5808	5790.5 ± 2.7
Ξ'_b	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	nsb	5946	–
Ξ^*_b	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	nsb	5975	–
Ω_b	$\frac{1}{2}^+$	0	1^+	ssc	6033	6071 ± 40
Ω^*_b	$\frac{3}{2}^+$	0	1^+	ssc	6063	–

Mixing does not have a great impact on the masses, but the admixture coefficients are large and mixing turns out to be very important for decay widths [9; 8; 10]. It is worth noting that physical states are very close to the states (B stands for Ξ or Ω in what follows)

$$\widehat{B}_{cb} = -\frac{\sqrt{3}}{2}B'_{cb} + \frac{1}{2}B_{cb} \quad , \quad \widehat{B}'_{cb} = \frac{1}{2}B'_{cb} + \frac{\sqrt{3}}{2}B_{cb} \tag{2}$$

in which it is the charm–light quark subsystem that has well defined total spin $S_{cq} = 1$ ($\widehat{B}_{cb}$) or $S_{cq} = 0$ ($\widehat{B}'_{cb}$).

2 Semileptonic decay widths

Expressions for the decay widths and the form factor decompositions of the hadronic matix elements can be found in Ref. [1]. For spin-1/2 to spin-1/2 transistions there are three vector (F_1, F_2, F_3) and three axial (G_1, G_2, G_3) form factors. For the case of spin-1/2 to spin-3/2 or spin-3/2 to spin-1/2 we have four vector (C_3^V, C_4^V, C_5^V, C_6^V) and four axial (C_3^A, C_4^A, C_5^A, C_6^A) form factors. For spin-3/2 to spin-3/2 a form factor decomposition can be found in Ref. [11]. However in this latter case we do not calculate the form factor themselves but just the vector and axial matrix elements.

Tables 2 and 3 summarize our results for the semileptonic decay widths for $c \to s$ and $c \to d$ transitions. Results in brackets correspond to the case where configuration mixing is ignored. As we see from the tables, in most of the cases, configuration mixing greatly affects the decay widths. We also see our results agree with the few existing previous calculations.

3 Heavy Quark Spin Symmetry constraints on the form factors

Heavy quark spin symmetry (HQSS) imposes a number of constrains among the form factors. Although these constraints are approximate, they can be used to make model independent predictions. These constraints are consequences of the spin symmetry for infinite heavy quark masses and can be derived using the trace formalism [12; 13]. This is explained in detail in Sec. IV of Ref. [1]. As an example we shall mention here some of the relations among form factors that hold at zero recoil, i.e. at $\omega = 1$, where ω is the product of the initial and final meson four-velocities. The constraints have been obtained for

Table 2 Decay widths for $c \to s$ transitions. Results where configuration mixing is not considered are shown in parentheses. The result with a † corresponds to the decay of the $\widehat{\Xi}_{cb}$ state. The result with an $*$ is our estimate from the total decay width and the branching ratio given in [4]. We have used $|V_{cs}| = 0.97345$.

	Γ [10^{-14} GeV]			
	This work	[2]	[3]	[4]
$\Xi^{(1)+}_{cbu} \to \Xi^{0}_{b}\, e^+\nu_e$	3.74 (3.45)	(3.4)		
$\Xi^{(2)+}_{cbu} \to \Xi^{0}_{b}\, e^+\nu_e$	2.65 (2.87)			
$\Xi^{(1)+}_{cbu} \to \Xi'^{0}_{b}\, e^+\nu_e$	3.88 (1.66)		$2.44 \div 3.28^\dagger$	
$\Xi^{(2)+}_{cbu} \to \Xi'^{0}_{b}\, e^+\nu_e$	1.95 (3.91)			
$\Xi^{(1)+}_{cbu} \to \Xi^{*\,0}_{b}\, e^+\nu_e$	1.52 (3.45)			
$\Xi^{(2)+}_{cbu} \to \Xi^{*\,0}_{b}\, e^+\nu_e$	2.67 (1.02)			
$\Xi^{(2)+}_{cbu} \to \Xi^{0}_{b}\, e^+\nu_e + \Xi'^{0}_{b}\, e^+\nu_e + \Xi^{*\,0}_{b}\, e^+\nu_e$	7.27 (7.80)			$(9.7 \pm 1.3)^*$
$\Xi^{*+}_{cbu} \to \Xi^{0}_{b}\, e^+\nu_e$	4.08			
$\Xi^{*+}_{cbu} \to \Xi'^{0}_{b}\, e^+\nu_e$	0.747			
$\Xi^{*+}_{cbu} \to \Xi^{*\,0}_{b}\, e^+\nu_e$	5.03			

	Γ [10^{-14} GeV]
$\Omega^{(1)\,0}_{cbs} \to \Omega^{-}_{b}\, e^+\nu_e$	7.21 (3.12)
$\Omega^{(2)\,0}_{cbs} \to \Omega^{-}_{b}\, e^+\nu_e$	3.49 (7.12)
$\Omega^{(1)\,0}_{cbs} \to \Omega^{*\,-}_{b}\, e^+\nu_e$	2.98 (6.90)
$\Omega^{(2)\,0}_{cbs} \to \Omega^{*\,-}_{b}\, e^+\nu_e$	5.50 (2.07)
$\Omega^{*\,0}_{cbs} \to \Omega^{-}_{b}\, e^+\nu_e$	1.35
$\Omega^{*\,0}_{cbs} \to \Omega^{*\,-}_{b}\, e^+\nu_e$	10.2

Table 3 Same as Table 2 for $c \to d$ decays. We have used $|V_{cd}| = 0.2252$.

	Γ [10^{-14} GeV]
$\Xi^{(1)+}_{cbu} \to \Lambda^{0}_{b}\, e^+\nu_e$	0.219 (0.196)
$\Xi^{(2)+}_{cbu} \to \Lambda^{0}_{b}\, e^+\nu_e$	0.136 (0.154)
$\Xi^{(1)+}_{cbu} \to \Sigma^{0}_{b}\, e^+\nu_e$	0.198 (0.0814)
$\Xi^{(2)+}_{cbu} \to \Sigma^{0}_{b}\, e^+\nu_e$	0.110 (0.217)
$\Xi^{(1)+}_{cbu} \to \Sigma^{*\,0}_{b}\, e^+\nu_e$	0.0807 (0.184)
$\Xi^{(2)+}_{cbu} \to \Sigma^{*\,0}_{b}\, e^+\nu_e$	0.147 (0.0556)
$\Xi^{*+}_{cbu} \to \Lambda^{0}_{b}\, e^+\nu_e$	0.235
$\Xi^{*+}_{cbu} \to \Sigma^{0}_{b}\, e^+\nu_e$	0.0399
$\Xi^{*+}_{cbu} \to \Sigma^{*\,0}_{b}\, e^+\nu_e$	0.246

	Γ [10^{-14} GeV]
$\Omega^{(1)\,0}_{cbs} \to \Xi^{-}_{b}\, e^+\nu_e$	0.179 (0.164)
$\Omega^{(2)\,0}_{cbs} \to \Xi^{-}_{b}\, e^+\nu_e$	0.120 (0.133)
$\Omega^{(1)\,0}_{cbs} \to \Xi'^{-}_{b}\, e^+\nu_e$	0.169 (0.0702)
$\Omega^{(2)\,0}_{cbs} \to \Xi'^{-}_{b}\, e^+\nu_e$	0.0908 (0.182)
$\Omega^{(1)\,0}_{cbs} \to \Xi^{*\,-}_{b}\, e^+\nu_e$	0.0690 (0.160)
$\Omega^{(2)\,0}_{cbs} \to \Xi^{*\,-}_{b}\, e^+\nu_e$	0.130 (0.0487)
$\Omega^{*\,0}_{cbs} \to \Xi^{-}_{b}\, e^+\nu_e$	0.196
$\Omega^{*\,0}_{cbs} \to \Xi'^{-}_{b}\, e^+\nu_e$	0.0336
$\Omega^{*\,0}_{cbs} \to \Xi^{*\,-}_{b}\, e^+\nu_e$	0.223

transitions involving states in which S_{cq} is well defined. Note the $\hat{B}^*_{cb}$ is the same as B^*_{cb}. For $\hat{B}_{cb}$, $\hat{B}'_{cb}$ or $\hat{B}^*_{cb}$ transistion to Λ_b or Ξ_b baryons one obtains the relations

$$
\begin{aligned}
&\hat{B}_{cb} \to \Lambda_b, \Xi_b : \qquad && F_1 + F_2 + F_3 = 0, \qquad && G_1 = \frac{1}{\sqrt{3}}\eta \\
&\hat{B}'_{cb} \to \Lambda_b, \Xi_b : \qquad && F_1 + F_2 + F_3 = \eta, \qquad && G_1 = 0 \\
&\hat{B}^*_{cb} \to \Lambda_b, \Xi_b : \qquad && -C_3^A \frac{M - M'}{M'} - C_4^A \frac{M(M - M')}{M'^2} + C_5^A = -\eta &&
\end{aligned}
\tag{3}
$$

where η is the corresponding Isgur-Wise function. This function is different for different ligth quark configurations in the initial and final baryons. Deviations from the above relations are expected for finite heavy quark masses. In the left panel of Fig. 1 we see our form factors approximately satisfy those constraints over the whole ω range available for the transitions. Similarly, for transitions from

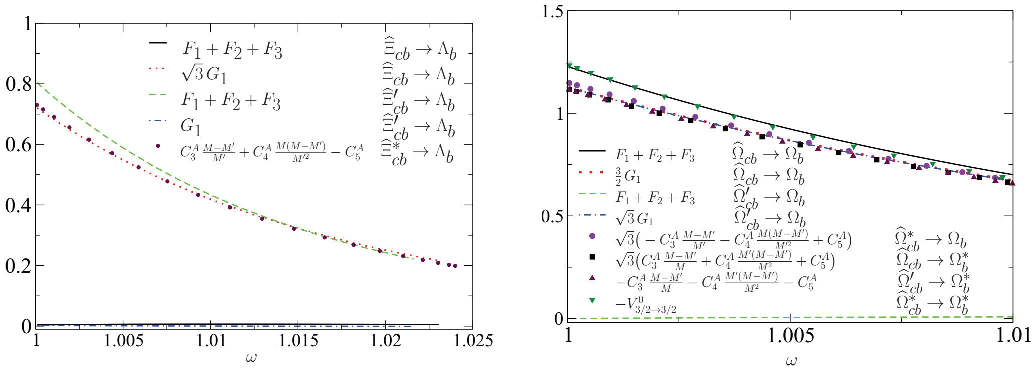

Fig. 1 Combinations of form factors that are constrained by HQSS as explained in the text.

initial $\hat{B}_{cb}$, $\hat{B}'_{cb}$, $\hat{B}^*_{cb}$ to final $\Sigma_b^{(*)}$, Ξ', Ξ^*, $\Omega^{(*)}$ baryons we have the zero recoil constraints

$$\hat{B}_{cb} \to \Sigma_b, \Xi'_b, \Omega_b : \qquad F_1+F_2+F_3 = \beta; \qquad G_1 = \frac{2}{3}\beta$$

$$\hat{B}'_{cb} \to \Sigma_b, \Xi_b, \Omega_b : \qquad F_1+F_2+F_3 = 0; \qquad G_1 = \frac{1}{\sqrt{3}}\beta$$

$$\begin{aligned}
\hat{B}^*_{cb} \to \Sigma_b, \Xi'_b, \Omega_b : &\qquad -C_3^A\frac{M-M'}{M'} - C_4^A\frac{M(M-M')}{M'^2} + C_5^A = \frac{1}{\sqrt{3}}\beta \\
\hat{B}_{cb} \to \Sigma^*_b, \Xi^*_b, \Omega^*_b : &\qquad C_3^A\frac{M-M'}{M'}C_4^A\frac{M(M-M')}{M'^2} + C_5^A = \frac{1}{\sqrt{3}}\beta \\
\hat{B}'_{cb} \to \Sigma^*_b, \Xi^*_b, \Omega^*_b : &\qquad C_3^A\frac{M-M'}{M'}C_4^A\frac{M(M-M')}{M'^2} + C_5^A = -\beta
\end{aligned} \tag{4}$$

For $\hat{B}*_{cb} \to \Sigma^*_b, \Xi^*_b, \Omega^*_b$ we get that the matrix element of the zero component of the vector part of the weak current equals $-\beta$ when evaluated between states with the same spin projection. As before, β is the corresponding Isgur-Wise function which depends on the initial and final light quark configurations. Again, as shown in the right panel of Fig. 1, we see the above HQSS constraints are approximately satisfied over the whole ω range.

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