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

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Introduction I

Baryon	J^P	I	S^π	Q. content	Mass [MeV]	
					Quark model [1]	Experiment PDG
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	–

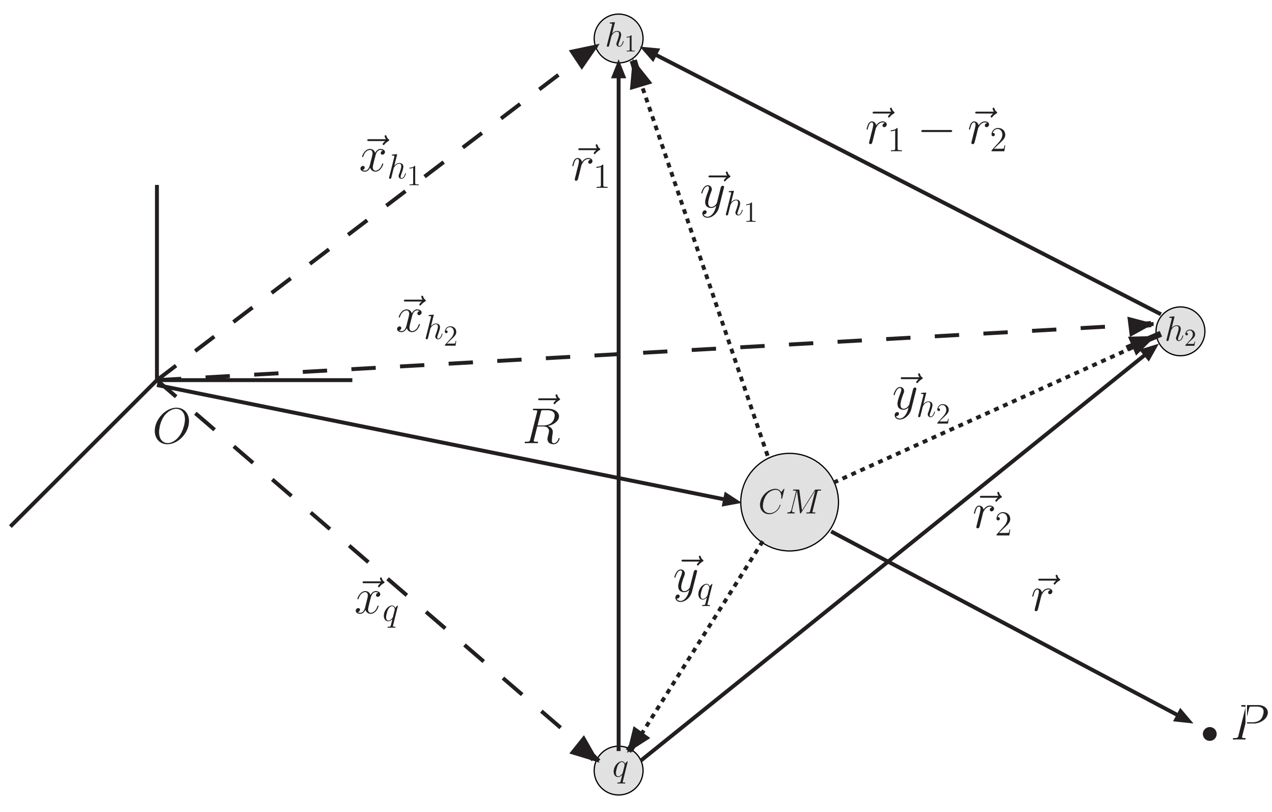
Introduction II

- Many theoretical determinations of the masses of doubly heavy baryons.
- Few studies of the decays
- In this work we concentrate in the study of the exclusive semileptonic $c \to d$ and $c \to s$ decay channels.
- We will study possible violations of the Heavy Quark Spin Symmetry relations among the form factors which one expects to be sizeable in the charm sector.

Three–body Hamiltonian I

$$H = -\frac{\vec{\nabla}^2_{\vec{R}}}{2\overline{M}} + H_{int} \qquad H_{int} = \overline{M} + \sum_{j=1,2} H_j^{sp} + V_{h_1,h_2}(\vec{r}_1 - \vec{r}_2, spin) - \frac{\vec{\nabla}_1 \cdot \vec{\nabla}_2}{m_q}$$

$$H_j^{sp} = -\frac{\vec{\nabla}^2_j}{2\mu_j} + V_{h_j,q}(\vec{r}_j, spin) \qquad \overline{M} = m_{h_1} + m_{h_2} + m_q \qquad \frac{1}{\mu_j} = \frac{1}{m_{h_j}} + \frac{1}{m_q}$$



Three–body Hamiltonian II

- We use the AL1 potential [C. Semay, B. Silvestre-Brac, Z. Phys. C**61**, 271 (1994)]

$$V_{ij}^{q\bar{q}}(r) = -\frac{\kappa}{r} + \lambda r - \Lambda + \frac{2\pi}{3m_i m_j}\kappa' \frac{e^{-r^2/x_0^2}}{\pi^{\frac{3}{2}} x_0^3}\vec{\sigma}_i\vec{\sigma}_j \quad ; \quad x_0(m_i, m_j) = A\left(\frac{2m_i m_j}{m_i + m_j}\right)$$

  Parameters adjusted to the light and heavy-light meson spectra.

- For qq pairs we use

$$V_{ij}^{qq}(r) = \frac{1}{2}\, V_{ij}^{q\bar{q}}(r)$$

  - Correct for the one-gluon exchange part
  - Phenomenologically successful for the confinement part

Baryon Wave Function

We are interested in ground state baryons (L=0)

- $\Xi_{h_1 h_2}, \Omega_{h_1 h_2}$:

$$\sum_{M_{S_h} M_{S_l}} \left(1 \frac{1}{2} \frac{1}{2} \middle| M_{S_h} M_{S_l} M_J \right) |h_1 h_2; 1 M_{S_h}\rangle_{S_h} \otimes \left| q; \frac{1}{2} M_{S_l} \right\rangle \phi_{h_1 h_2 q}(r_1, r_2, r_{12})$$

- $\Xi'_{h_1 h_2}, \Omega'_{h_1 h_2}$:

$$|h_1 h_2; 00\rangle_{S_h} \otimes \left| q; \frac{1}{2} M_{S_l} \right\rangle \phi_{h_1 h_2 q}(r_1, r_2, r_{12})$$

- $\Xi^*_{h_1 h_2}, \Omega^*_{h_1 h_2}$:

$$\sum_{M_{S_h} M_{S_l}} \left(1 \, \frac{1}{2} \frac{3}{2} \, \middle| M_{S_h} \; M_{S_l} M_J \right) |h_1 h_2; 1 M_{S_h}\rangle_{S_h} \otimes \left| q; \frac{1}{2} M_{S_l} \right\rangle \phi_{h_1 h_2 q}(r_1, r_2, r_{12})$$

Variational Ansatz

- We use a simple ansatz for the spatial wave function:

$$\phi_{h_1,h_2,q}(r_1,r_2,r_{12}) = N\phi^q_{h_1}(r_1)\phi^q_{h_2}(r_2)F(r_{12})$$

  - $\phi^q_{h_j}(r_j) = (1+\alpha_j\, r_j)\,\psi^q_{h_j}(r_j)$
    Ground state wave function $\psi^q_{h_j}(r_j)$ for the relative motion of the light–quark heavy–quark system for the chosen potential, corrected at large distances.
  - Jastrow correlation function

$$F(r_{12}) = \sum_{j=1}^{4} a_j\, e^{-b_j^2\,(r_{12}+d_j)^2} \qquad a_1 = 1$$

  - N: Normalization constant
- Parameters of the variational ansatz adjusted so that $\langle B\,|H|\,B\rangle$ is minimized

Configuration mixing in cb baryons

- The hyperfine interaction between the light quark and any of the heavy ones can admix $S = 0$ and $S = 1$ states.
- This is due to the finite value of the heavy quark masses.

$$\Xi_{cb}^{(1)} = -0.902\Xi'_{cb} + 0.431\Xi_{cb}; \quad M_{\Xi_{cb}^{(1)}} = 6967\,\mathrm{MeV},$$

$$\Xi_{cb}^{(2)} = 0.431\Xi'_{cb} + 0.902\Xi_{cb}; \quad M_{\Xi_{cb}^{(2)}} = 6919\,\mathrm{MeV}.$$

$$\Omega_{cb}^{(1)} = -0.899\Omega'_{cb} + 0.437\Omega_{cb}; \quad M_{\Omega_{cb}^{(1)}} = 7046\,\mathrm{MeV},$$

$$\Omega_{cb}^{(2)} = 0.437\Omega'_{cb} + 0.899\Omega_{cb}; \quad M_{\Omega_{cb}^{(2)}} = 7005\,\mathrm{MeV},$$

Semileptonic Decay Width I

- Semileptonic decay width

$$\Gamma = |V_{cl}|^2 \frac{G_F^2}{8\pi^4} \frac{M'^2}{M} \int \sqrt{w^2-1}\, \mathcal{L}^{\alpha\beta}(q) \mathcal{H}_{\alpha\beta}(P,P')\, dw$$

- Hadronic tensor

$$\mathcal{H}^{\alpha\beta}(P,P') = \frac{1}{2J+1} \sum_{r,r'} \left\langle B', r'\ \vec{P}\,' \middle| J_{cl}^{\alpha}(0) \middle| B, r\ \vec{P} \right\rangle \times \left\langle B', r'\ \vec{P}\,' \middle| J_{cl}^{\beta}(0) \middle| B, r\ \vec{P} \right\rangle^*$$

Form Factor Decomposition

- $1/2 \to 1/2$

$$\left\langle B'(1/2), r'\ \vec{P}\,' \,\middle|\, \overline{\Psi}_l(0)\gamma^\mu(1-\gamma_5)\Psi_c(0) \,\middle|\, B(1/2), r\ \vec{P} \right\rangle = \bar{u}^{B'}_{r'}(\vec{P}\,')\Big\{\gamma^\mu\left[F_1(w)-\gamma_5 G_1(w)\right]+$$
$$v^\mu\left[F_2(w)-\gamma_5 G_2(w)\right]+v'^\mu\left[F_3(w)-\gamma_5 G_3(w)\right]\Big\}u^B_r(\vec{P}\,)$$

- $1/2 \to 3/2$

$$\left\langle B'(3/2), r'\vec{P}' \,\middle|\, \overline{\Psi}_l(0)\gamma^\mu(1-\gamma_5)\Psi_c(0) \,\middle|\, B(1/2), r\ \vec{P}\, \right\rangle = \bar{u}^{B'}_{\lambda\, r'}(\vec{P}\,')\,\Gamma^{\lambda\mu}(P,P')\,u^B_r(\vec{P}\,)$$

$$\Gamma^{\lambda\mu}(P,P') = \left[\frac{C_3^V(\omega)}{M}(g^{\lambda\,\mu}\not{q} - q^\lambda\gamma^\mu) + \frac{C_4^V(\omega)}{M^2}(g^{\lambda\,\mu}qP' - q^\lambda P'^\mu) + \right.$$
$$\left.\frac{C_5^V(\omega)}{M^2}(g^{\lambda\,\mu}qP - q^\lambda P^\mu) + C_6^V(\omega)g^{\lambda\,\mu}\right]\gamma_5$$
$$+\left[\frac{C_3^A(\omega)}{M}(g^{\lambda\,\mu}\not{q} - q^\lambda\gamma^\mu) + \frac{C_4^A(\omega)}{M^2}(g^{\lambda\,\mu}qP' - q^\lambda P'^\mu) + C_5^A(\omega)g^{\lambda\,\mu} + \frac{C_6^A(\omega)}{M^2}q^\lambda q^\mu\right]$$

Semileptonic Decay Width II

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

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

Semileptonic Decay Width III

	Γ [10^{-14} GeV]
$\Xi_{cbu}^{(1)+} \longrightarrow \Lambda_b^0 e^+ \nu_e$	0.219 (0.196)
$\Xi_{cbu}^{(2)+} \longrightarrow \Lambda_b^0 e^+ \nu_e$	0.136 (0.154)
$\Xi_{cbu}^{(1)+} \longrightarrow \Sigma_b^0 e^+ \nu_e$	0.198 (0.0814)
$\Xi_{cbu}^{(2)+} \longrightarrow \Sigma_b^0 e^+ \nu_e$	0.110 (0.217)
$\Xi_{cbu}^{(1)+} \longrightarrow \Sigma_b^{*0} e^+ \nu_e$	0.0807 (0.184)
$\Xi_{cbu}^{(2)+} \longrightarrow \Sigma_b^{*0} e^+ \nu_e$	0.147 (0.0556)
$\Xi_{cbu}^{*+} \longrightarrow \Lambda_b^0 e^+ \nu_e$	0.235
$\Xi_{cbu}^{*+} \longrightarrow \Sigma_b^0 e^+ \nu_e$	0.0399
$\Xi_{cbu}^{*+} \longrightarrow \Sigma_b^{*0} e^+ \nu_e$	0.246

Semileptonic Decay Width IV

	Γ [10^{-14} GeV]
$\Omega_{cbs}^{(1)0} \longrightarrow \Xi_b^- e^+ \nu_e$	0.179 (0.164)
$\Omega_{cbs}^{(2)0} \longrightarrow \Xi_b^- e^+ \nu_e$	0.120 (0.133)
$\Omega_{cbs}^{(1)0} \longrightarrow \Xi_b^{\prime -} e^+ \nu_e$	0.169 (0.0702)
$\Omega_{cbs}^{(2)0} \longrightarrow \Xi_b^{\prime -} e^+ \nu_e$	0.0908 (0.182)
$\Omega_{cbs}^{(1)0} \longrightarrow \Xi_b^{*-} e^+ \nu_e$	0.0690 (0.160)
$\Omega_{cbs}^{(2)0} \longrightarrow \Xi_b^{*-} e^+ \nu_e$	0.130 (0.0487)
$\Omega_{cbs}^{*0} \longrightarrow \Xi_b^- e^+ \nu_e$	0.196
$\Omega_{cbs}^{*0} \longrightarrow \Xi_b^{\prime -} e^+ \nu_e$	0.0336
$\Omega_{cbs}^{*0} \longrightarrow \Xi_b^{*-} e^+ \nu_e$	0.223

Heavy Quark Spin Symmetry

- In baryons with two quarks Heavy Quark Symmetry cannot be applied...
- ... but Heavy Quark Spin Symmetry still holds.
- At zero recoil, where spin symmetry should work best, HQSS reduces the number of independent form factor.

HQSS relations near zero recoil

A number of relations between the form factors can be obtained (see, for instance Section IV of PRD 85 (2012) 094035). As an example, we shall mention

- $\hat{B}_{cb} \to \Lambda_b, \Xi_b$

$$F_1 + F_2 + F_3 = 0, \quad G_1 = \frac{\eta}{\sqrt{3}}$$

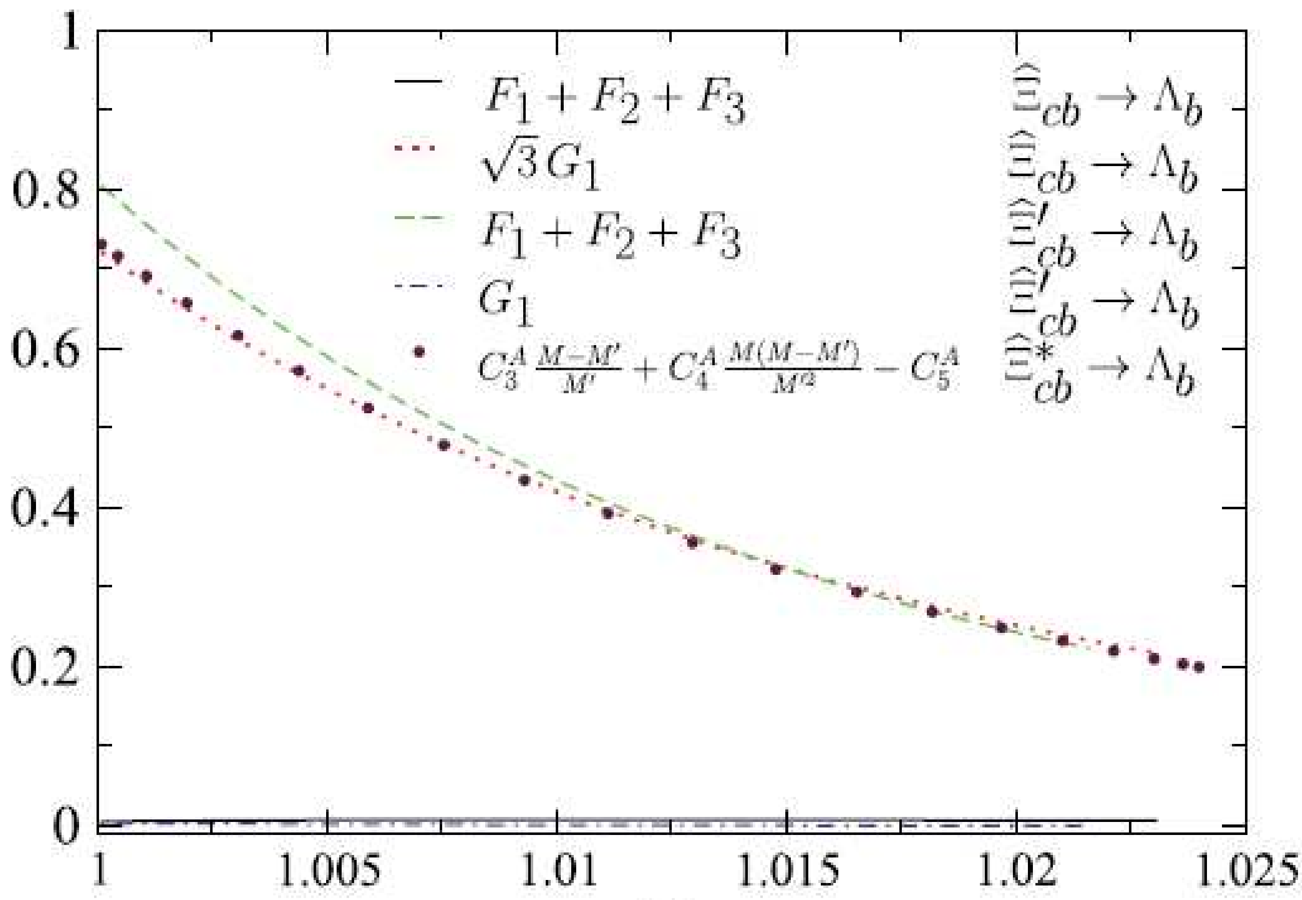
- $\hat{B}'_{cb} \to \Lambda_b, \Xi_b$

$$F_1 + F_2 + F_3 = \eta, \quad G_1 = 0$$

- $\hat{B}^*_{cb} \to \Lambda_b, \Xi_b$

$$-C_3^A \frac{M - M'}{M'} - C_4^A \frac{M(M - M')}{M'^2} + C_5^A = -\eta$$

Heavy Quark Spin Symmetry



Summary

- We have done a systematic study of all dominant and subdominant $c \to d, s$ decays of bc baryons.
- We have worked in the context of a simple CQM scheme, already tested in the past.
- We have derived HQSS relations among the form factors at zero recoil. We have tested our form factors against these relations.