Role of hyperfine mixing in b → c semileptonic decays of doubly-heavy baryons[*]

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Abstract We analyze the effects of hyperfine mixing in b → c semileptonic decays of doubly heavy baryons. We qualitatively confirm the results by W. Roberts and M. Pervin in Int. J. Mod. Phys. A, 2009, 24: 2401–2413, finding that mixing has a great impact on those transitions. However, predictions without mixing differ by a factor of 2 and this discrepancy translates to the mixed case where large differences in decay widths are observed between the two calculations.

Key words doubly-heavy baryons, semileptonic decay, hyperfine mixing

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1 Introduction

According to heavy quark spin symmetry, in the infinite heavy quark mass limit, one can select the total spin (S_h) of the heavy quark subsystem of a doubly heavy baryon to be well defined [1]. This result has been used as a basis for the usual classification scheme of doubly heavy baryons. In Table 1 we list the ground state doubly heavy baryons with quantum numbers $J^\pi = \frac{1}{2}^+$, $\frac{3}{2}^+$ that are included in this study.

Hyperfine interaction between the light and any of the heavy quarks can admix components with both $S_h = 0$ and $S_h = 1$ in the wave function. The mixing should be very small in the bb and cc sectors as it will imply higher radial excitations or larger angular momentum. However, mixing could be particularly important for baryons with bc heavy quark content where one expects the actual physical Ξ (Ω) states to be admixtures of the Ξ_{bc}, Ξ'_{bc} $(\Omega_{bc}, \Omega'_{bc})$ ones given in Table 1. This mixing gives rise to small changes in the masses but, as suggested in Ref. [2], it could have a great impact on the widths of decays involving those states. This has been investigated in Ref. [3] using harmonic oscillator wave functions as an expanding basis. Here we shall try to confirm their findings using our variational wave functions described in Ref. [4] and obtained with the use of the AL1 potential of Ref. [5]. All the details on the calculations can be found in Ref. [6] and references therein.

Table 1. Quantum numbers and quark content of doubly heavy baryons.

baryon	quark content (l=u,d)	S_h	J^π	baryon	quark content	S_h	J^π
Ξ_{cc}	{c c} l	1	$1/2^+$	Ω_{cc}	{c c} s	1	$1/2^+$
Ξ^*_{cc}	{c c} l	1	$3/2^+$	Ω^*_{cc}	{c c} s	1	$3/2^+$
Ξ_{bb}	{b b} l	1	$1/2^+$	Ω_{bb}	{b b} s	1	$1/2^+$
Ξ^*_{bb}	{b b} l	1	$3/2^+$	Ω^*_{bb}	{b b} s	1	$3/2^+$
Ξ_{bc}	{b c} l	1	$1/2^+$	Ω_{bc}	{b c} s	1	$1/2^+$
Ξ^*_{bc}	{b c} l	1	$3/2^+$	Ω^*_{bc}	{b c} s	1	$3/2^+$
Ξ'_{bc}	[b c] l	0	$1/2^+$	Ω'_{bc}	[b c] s	0	$1/2^+$

2　Results and discussion

2.1　Masses for unmixed states

Our results for the masses are given in Table 2. We compare them with the results obtained in Ref. [7] using a relativistic quark model that assumes a light quark-heavy diquark structure, and in the above mentioned Ref. [2] where they use a nonrelativistic approach with harmonic oscillator wave functions. The agreement with the calculation in Ref. [7] is very good for Ξ baryons whereas for Ω baryons their masses are some $50\sim 90$ MeV larger. The masses obtained in Ref. [2] are always larger than ours by $50\sim 180$ MeV. On the experimental side the SELEX Collaboration claimed evidence for the Ξ_{cc}^{+} baryon, in the $\Lambda_c^+ K^- \pi^+$ and pD^+K^- decay modes, with a mass of $M_{\Xi_{cc}^+} = 3519 \pm 1$ MeV/c^2 [8], a 100 MeV smaller than most theoretical predictions. No other experimental collaboration has found evidence for doubly charmed baryons so far and, at present, the Ξ_{cc}^{+} has only a one star status.

Table 2.　Masses (in MeV) for unmixed states.

	this work	[7]	[2]
$M_{\Xi_{cc}}$	3613	3620	3676
$M_{\Xi_{cc}^*}$	3707	3727	3753
$M_{\Xi_{bb}}$	10198	10202	10340
$M_{\Xi_{bb}^*}$	10237	10237	10367
$M_{\Xi_{bc}}$	6928	6933	7020
$M_{\Xi_{bc}'}$	6958	6963	7044
$M_{\Xi_{bc}^*}$	6996	6980	7078
$M_{\Omega_{cc}}$	3712	3778	3815
$M_{\Omega_{cc}^*}$	3795	3872	3876
$M_{\Omega_{bb}}$	10269	10359	10454
$M_{\Omega_{bb}^*}$	10307	10389	10486
$M_{\Omega_{bc}}$	7013	7088	7147
$M_{\Omega_{bc}'}$	7038	7116	7166
$M_{\Omega_{bc}^*}$	7075	7130	7191

2.2　Decay widths for unmixed states

Our model to evaluate b→c semileptonic decays of doubly heavy baryons is described in Ref. [4]. We use a spectator approximation in which any of the b quarks in the initial state can decay into any of the c quarks in the final state. This, together with the right normalization for baryon states containing two equal heavy quarks, gives an extra factor $\sqrt{2}$ in the transition amplitude when compared to the similar b→c decay in baryons with just one heavy quark.

The results that we obtain are shown in Table 3 where for comparison we also show the results in

Refs. [9, 10], obtained within different relativistic approaches, and in the nonrelativistic calculation of Ref. [3]. Our results are in a global fair agreement with the ones in Ref. [9]. As for the other relativistic calculation in Ref. [10], the agreement is fair for transitions with a bc baryon in the initial state but there is an approximate factor of 2 discrepancy for transitions with a bc baryon in the final state. The nonrelativistic calculation in Ref. [3] also gives results that are roughly a factor of 2 smaller than ours for all decays. A very interesting feature of the decay widths shown in Table 3 is that they are very different for transitions involving Ξ_{bc} or Ξ_{bc}' (Ω_{bc} or Ω_{bc}'). This means, as suggested in Ref. [2], that mixing in those states, provided the admixture coefficients are large, can have a great impact on the decay widths.

Table 3.　Semileptonic decay widths (in 10^{-14} GeV) for unmixed states. We use $|V_{cb}| = 0.0413$. l=e, μ.

	this work	[9]	[10]	[3]
$\Gamma(\Xi_{bb}^* \to \Xi_{bc}' l\bar{\nu}_l)$	1.08	0.82	0.36 ± 0.10	–
$\Gamma(\Xi_{bb}^* \to \Xi_{bc} l\bar{\nu}_l)$	0.36	0.28	0.14 ± 0.04	–
$\Gamma(\Xi_{bb} \to \Xi_{bc}' l\bar{\nu}_l)$	1.09	0.82	0.43 ± 0.12	0.41
$\Gamma(\Xi_{bb} \to \Xi_{bc} l\bar{\nu}_l)$	2.00	1.63	0.80 ± 0.30	0.69
$\Gamma(\Xi_{bc}' \to \Xi_{cc} l\bar{\nu}_l)$	1.36	0.88	1.10 ± 0.32	–
$\Gamma(\Xi_{bc} \to \Xi_{cc} l\bar{\nu}_l)$	2.57	2.30	2.10 ± 0.70	1.38
$\Gamma(\Xi_{bc}' \to \Xi_{cc}^* l\bar{\nu}_l)$	2.35	1.70	2.01 ± 0.62	–
$\Gamma(\Xi_{bc} \to \Xi_{cc}^* l\bar{\nu}_l)$	0.75	0.72	0.64 ± 0.19	0.52
$\Gamma(\Omega_{bb}^* \to \Omega_{bc}' l\bar{\nu}_l)$	1.14	0.85	0.42 ± 0.14	–
$\Gamma(\Omega_{bb}^* \to \Omega_{bc} l\bar{\nu}_l)$	0.38	0.29	0.15 ± 0.05	–
$\Gamma(\Omega_{bb} \to \Omega_{bc}' l\bar{\nu}_l)$	1.16	0.83	0.48 ± 0.12	0.51
$\Gamma(\Omega_{bb} \to \Omega_{bc} l\bar{\nu}_l)$	2.15	1.70	0.86 ± 0.32	0.92
$\Gamma(\Omega_{bc}' \to \Omega_{cc} l\bar{\nu}_l)$	1.36	0.95	0.98 ± 0.28	–
$\Gamma(\Omega_{bc} \to \Omega_{cc} l\bar{\nu}_l)$	2.58	2.48	1.88 ± 0.62	1.54
$\Gamma(\Omega_{bc}' \to \Omega_{cc}^* l\bar{\nu}_l)$	2.35	1.83	1.93 ± 0.60	–
$\Gamma(\Omega_{bc} \to \Omega_{cc}^* l\bar{\nu}_l)$	0.76	0.74	0.62 ± 0.19	0.56

2.3　Results with mixing

We obtain the mixed bc states by diagonalization of the corresponding mass matrices. In our calculation the mixed states and masses are given by

$$\Xi_{bc}^{(1)} = 0.902\Xi_{bc}' + 0.431\Xi_{bc},\ M_{\Xi_{bc}^{(1)}} = 6967\ \text{MeV},$$

$$\Xi_{bc}^{(2)} = -0.431\Xi_{bc}' + 0.902\Xi_{bc},\ M_{\Xi_{bc}^{(2)}} = 6919\ \text{MeV},$$

$$\Omega_{bc}^{(1)} = 0.899\Omega_{bc}' + 0.437\Omega_{bc},\ M_{\Omega_{bc}^{(1)}} = 7046\ \text{MeV},$$

$$\Omega_{bc}^{(2)} = -0.437\Omega_{bc}' + 0.899\Omega_{bc},\ M_{\Omega_{bc}^{(2)}} = 7005\ \text{MeV}.$$

$$(1)$$

By comparison to the unmixed results shown in Table 2, we see the masses change but very little when

mixing is taken in to account. However, as shown in Eq. (1), the admixture is important and it can affect the decay widths.

Note that these mixed states are close to the states (in the what follows $B \equiv \Xi, \Omega$)

$$B_{bc}^{(1)} \approx \left(|qc;1\rangle \otimes |b; \frac{1}{2}\rangle \right)^{J=1/2} \equiv \frac{\sqrt{3}}{2} B'_{bc} + \frac{1}{2} B_{bc},$$

$$B_{bc}^{(2)} \approx \left(|qc;0\rangle \otimes |b; \frac{1}{2}\rangle \right)^{J=1/2} \equiv -\frac{1}{2} B'_{bc} + \frac{\sqrt{3}}{2} B_{bc}, \quad (2)$$

in which the light and the c quark couple to well defined spin 1 or 0.

Table 4. Semileptonic decay widths (in 10^{-14} GeV) for mixed states. We use $|V_{cb}| = 0.0413$. l=e, μ.

	this work	[3]
$\Gamma(\Xi_{bb}^* \to \Xi_{bc}^{(1)} l\bar{\nu}_l)$	0.47	–
$\Gamma(\Omega_{bb}^* \to \Omega_{bc}^{(1)} l\bar{\nu}_l)$	0.48	–
$\Gamma(\Xi_{bb}^* \to \Xi_{bc}^{(2)} l\bar{\nu}_l)$	0.99	–
$\Gamma(\Omega_{bb}^* \to \Omega_{bc}^{(2)} l\bar{\nu}_l)$	1.06	–
$\Gamma(\Xi_{bb} \to \Xi_{bc}^{(1)} l\bar{\nu}_l)$	2.21	0.95
$\Gamma(\Omega_{bb} \to \Omega_{bc}^{(1)} l\bar{\nu}_l)$	2.36	0.99
$\Gamma(\Xi_{bb} \to \Xi_{bc}^{(2)} l\bar{\nu}_l)$	0.85	0.33
$\Gamma(\Omega_{bb} \to \Omega_{bc}^{(2)} l\bar{\nu}_l)$	0.91	0.30
$\Gamma(\Xi_{bc}^{(1)} \to \Xi_{cc} l\bar{\nu}_l)$	0.38	–
$\Gamma(\Omega_{bc}^{(1)} \to \Omega_{cc} l\bar{\nu}_l)$	0.37	–
$\Gamma(\Xi_{bc}^{(2)} \to \Xi_{cc} l\bar{\nu}_l)$	3.51	1.92
$\Gamma(\Omega_{bc}^{(2)} \to \Omega_{cc} l\bar{\nu}_l)$	3.52	1.99
$\Gamma(\Xi_{bc}^{(1)} \to \Xi_{cc}^* l\bar{\nu}_l)$	3.14	–
$\Gamma(\Omega_{bc}^{(1)} \to \Omega_{cc}^* l\bar{\nu}_l)$	3.14	–
$\Gamma(\Xi_{bc}^{(2)} \to \Xi_{cc}^* l\bar{\nu}_l)$	0.017	0.026
$\Gamma(\Omega_{bc}^{(2)} \to \Omega_{cc}^* l\bar{\nu}_l)$	0.014	0.013

The new decay widths involving the mixed states

$\Xi_{bc}^{(1)}, \Xi_{bc}^{(2)}$ and $\Omega_{bc}^{(1)}, \Omega_{bc}^{(2)}$ are now given in Table 4. We see rather big changes from the values in Table 3 where unmixed states were used. Special attention deserves the $B_{bc}^{(2)} \to B_{cc}^*$ transitions where the width reduces by a large factor of 44 (54) for the $\Xi_{bc}^{(2)} \to \Xi_{cc}^*$ ($\Omega_{bc}^{(2)} \to \Omega_{cc}^*$) decay compared to the unmixed case. This can be easily understood by taking into account that

$$B_{bc}^{(2)} \approx \left(|qc;0\rangle \otimes |b; \frac{1}{2}\rangle \right)^{J=1/2}.$$

In the latter state the light and c quarks are coupled to spin 0, whereas in the B_{cc}^* the light and any of the c quarks are in a relative spin 1 state. In any spectator calculation, as the ones here and in Ref. [3], the amplitude for the

$$\left(|qc;0\rangle \otimes |b; \frac{1}{2}\rangle \right)^{J=1/2} \to B_{cc}^*$$

transition cancels due to the orthogonality of the different spin states of the spectator quarks in the initial and final baryons. The fact that $B_{bc}^{(2)}$ slightly deviates from

$$\left(|qc;0\rangle \otimes |b; \frac{1}{2}\rangle \right)^{J=1/2}$$

produces a non zero, but small, decay width.

3 Conclusions

We qualitatively confirm the findings in Ref. [3] as to the relevance of hyperfine mixing in b → c semileptonic decays of doubly heavy baryons. On the other hand the absolute predictions are quite different. This is a reflection of the approximate factor of 2 difference we already found in Table 3 for unmixed states.

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