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FCNC decays of spin-1/2 double heavy baryons to spin-3/2 single heavy baryons

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Abstract. In recent years, there have been many discoveries in the spectroscopy of hadrons containing heavy quarks. Almost all baryons containing a single heavy quark are discovered in experiments. The quark model predicts the existence of many baryons with double heavy quarks. Among the possible double heavy baryons, only Ξ_{cc}^{+} and Ξ_{cc}^{++} have been experimentally observed in LHCb. Flavor-changing neutral current (FCNC) processes represent a promising platform for precise testing of SM and looking for new physics beyond the SM. In this study, the weak decays of spin-1/2 double heavy baryons to spin-3/2 single heavy baryons induced by FCNC are studied within the light cone QCD sum rules method. First, the transition form factors of $\Xi_{bb}^{0,-} \to \Xi_b^{*0,-}\bar{\ell}\ell$, $\Xi_{bb}^{0,-} \to \Sigma_b^{*0,-}\bar{\ell}\ell$, $\Omega_{bb}^{-} \to \Xi_b^{*-}\bar{\ell}\ell$, $\Omega_{bb}^{-} \to \Sigma_b^{*-}\bar{\ell}\ell$ decays are calculated. Then, the corresponding decay widths are estimated using the results for the form factors.

1 Introduction

Development of the experimental technique allowed the discovery of baryons containing a single heavy quark. The quark model predicts the existence of the baryons containing two heavy quarks. Despite the enormous efforts of experimentalists, only Ξ_{cc}^{+} and Ξ_{cc}^{++} baryons are observed [1][2]. Remaining doubly heavy baryons expected their own discoveries. Therefore, a comprehensive theoretical study of their properties, strong, electromagnetic, and weak decay, receives special attention. Among these decays, weak decays governed by flavor-changing neutral current (FCNC) represent promising ones; this is due to the fact that in the Standard Model (SM), at tree level, these decays are forbidden and take place only at the loop level. Therefore, these decays are very sensitive to the gauge structure of the effective Hamiltonian. At the same time, these decays are good places for searching for new physics. At present work, we study the weak FCNC decays of spin-1/2 doubly heavy baryons to spin-3/2 single heavy baryons within light-cone sum rules.

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2 Light-cone sum rules of the decay form factors

The flavor-changing neutral transitions ($b \to (d$ or $s)\bar{\ell}\ell$) are governed by the weak effective Hamiltonian [3]:

$$\mathcal{H}^{eff} = -4\frac{G_F}{\sqrt{2}}\left[C_7^{eff}O_7 + C_9^{eff}O_9 + C_{10}O_{10}\right] \tag{1}$$

where

$$\begin{aligned} O_7 &= \frac{e}{16\pi^2}\sum_q m_Q\left(\bar{q}_L\sigma_{\mu\nu}Q_R\right)F^{\mu\nu} \\ O_9 &= \frac{e^2}{16\pi^2}\sum_q\left(\bar{q}_L\gamma_\mu Q_L\right)\left(\bar{\ell}\gamma^\mu\ell\right) \\ O_{10} &= \frac{e^2}{16\pi^2}\sum_q\left(\bar{q}_L\gamma_\mu Q_L\right)\left(\bar{\ell}\gamma^\mu\gamma_5\ell\right) \end{aligned} \tag{2}$$

Wilson coefficients in the eq. 1 are given in[3]. To examine the FCNC decays of $\left(\frac{1}{2}\right)_{QQ} \to \left(\frac{3}{2}\right)_Q\bar{\ell}\ell$, the matrix element $\left\langle\left(\frac{3}{2}\right)_Q\middle|\mathcal{H}^{eff}\middle|\left(\frac{1}{2}\right)_{QQ}\right\rangle$ is needed. The matrix elements contain $\left\langle\left(\frac{3}{2}\right)_Q\middle|\bar{q}\gamma_\mu\left(\gamma_5\right)Q\middle|\left(\frac{1}{2}\right)_{QQ}\right\rangle$, $\left\langle\left(\frac{3}{2}\right)_Q\middle|\bar{q}\sigma_{\mu\nu}Q\middle|\left(\frac{1}{2}\right)_{QQ}\right\rangle$ which can be written in terms of the form factors as follow[4]:

$$\begin{aligned} \left\langle B^*_{Q^{(\prime)}}(p)\middle|\bar{q}\gamma_\mu\left(\gamma_5\right)Q^{(\prime)}\middle|B_{QQ^{(\prime)}}(p')\right\rangle = \bar{u}^\lambda_{Q^{(\prime)}}(p)\left(\gamma_5\right)\Big[&(q_\lambda p_\mu - pq g_{\lambda\mu})F_1^V + (q_\lambda\gamma_\mu - \not{q}g_{\lambda\mu})F_2^V \\ &+ (q_\lambda q_\mu - q^2 g_{\lambda\mu})F_3^V + q_\lambda q_\mu F_0^V\Big]u_{QQ^{(\prime)}}(p') \end{aligned} \tag{3}$$

$$\begin{aligned} \left\langle B^*_{Q^{(\prime)}}(p)\middle|\bar{q}i\sigma_{\mu\nu}Q^{(\prime)}\middle|B_{QQ^{(\prime)}}(p')\right\rangle = \bar{u}^\lambda_{Q^{(\prime)}}(p)\Big[&-iq_\lambda\sigma_{\mu\nu}F_1^T + q_\lambda\left(\gamma_\mu p_\nu - \gamma_\nu p_\mu\right)F_2^T \\ &+ q_\lambda\left(\gamma_\mu q_\nu - \gamma_\nu q_\mu\right)F_3^T + q_\lambda\left(p_\mu q_\nu - p_\nu q_\mu\right)F_4^T \\ &+ \left(g_{\mu\lambda}\gamma_\nu - g_{\nu\lambda}\gamma_\mu\right)F_5^T + \left(g_{\mu\lambda}p_\nu - g_{\nu\lambda}p_\mu\right)F_6^T \\ &+ \left(g_{\mu\lambda}q_\nu - g_{\nu\lambda}q_\mu\right)F_7^T\Big]\gamma_5 u_{QQ^{(\prime)}}(p') \end{aligned} \tag{4}$$

Relation between the form-factors with the contracted q^ν $\left(T_i^{V(A)}\right)$ and generic form-factors $\left(F_i^T\right)$ can be found in [4]. To calculate the form factors given in eqs 3 and 4 using light-cone sum rules, we use the following correlation function:

$$\Pi_\Gamma = i\int d^4x e^{iqx}\left\langle 0\middle|\mathcal{T}\left\{J_\Gamma^\dagger(x)j_{QQ}(0)\right\}\middle|B^*(p)\right\rangle \tag{5}$$

where j_{QQ} is the interpolating current of the spin-1/2 double heavy baryons, J_Γ is the transition current, namely $\bar{q}\gamma_\mu Q$, $\bar{q}\gamma_\mu\gamma_5 Q$ and $\bar{q}\sigma_{\mu\nu}Q$, and $B^*(p)$ denotes the spin-3/2 single heavy baryon state with momentum p.

2.1 Phenomenological side of the correlation function

Saturating the correlation function with states carrying the same quantum numbers of B_{QQ} states and separating the ground state contribution, we get

$$\Pi_\Gamma = \frac{\left\langle 0\middle|j_{QQ}(0)\middle|B_{QQ}(p')\right\rangle\left\langle B_{QQ}(p')\middle|J_\Gamma^\dagger\middle|B_Q^*(p)\right\rangle}{p'^2 - M_h^2} + \ldots \tag{6}$$

where ... means higher state and continuum contributions.

The matrix element $\langle 0 \big| j_{QQ}(0) \big| B_{QQ}(p') \rangle$ is defined as

$$\langle 0 \big| j_{QQ}(0) \big| B_{QQ}(p') \rangle = \lambda_{QQ} u_{QQ}(p') \tag{7}$$

where λ_{QQ} is the residue of the spin-1/2 baryon. The residues of the doubly heavy spin-1/2 baryons are calculated in [5]. Using the general definition $\left\langle B_{QQ}(p') \middle| J_\Gamma^\dagger \middle| B_Q^*(p) \right\rangle = \bar{u}_{QQ}(p') O_\Gamma^\lambda u_Q^\lambda(p)$ and performing summation over the spins of B_{QQ} baryons we get the expressions of the hadronic part of the correlation functions:

$$\begin{aligned} \Pi_\mu^V = \frac{\lambda_{QQ}}{p'^2 - m_{1/2}^2} \Big[& (F_0^V + F_3^V) q_\lambda q_\mu \not{q} + F_1^V p_\mu q_\lambda \not{q} + \not{q} g_{\mu\lambda} (-q^2 F_3^V) \\ & - F_2^V \gamma_\mu q_\lambda \not{q} + (\gamma_\mu q_\lambda - \not{q} g_{\mu\lambda})(m_{1/2} + m_{3/2}) F_2^V + \cdots \Big] \gamma_5 u_Q^\lambda(p) \end{aligned} \tag{8}$$

$$\begin{aligned} \Pi_\mu^A = \frac{\lambda_{QQ}}{p'^2 - m_{1/2}^2} \Big[& (F_0^A + F_3^A) q_\lambda q_\mu \not{q} + F_1^A p_\mu q_\lambda \not{q} + \not{q} g_{\mu\lambda} (-q^2 F_3^A) \\ & - F_2^A \gamma_\mu q_\lambda \not{q} + (\gamma_\mu q_\lambda - \not{q} g_{\mu\lambda})(m_{1/2} - m_{3/2}) F_2^A + \cdots \Big] u_Q^\lambda(p) \end{aligned} \tag{9}$$

$$\begin{aligned} \Pi_{\mu\nu}^T = \frac{\lambda_{QQ}}{p'^2 - M_1^2} \Big[& F_1^T q_\lambda (\gamma_\mu \gamma_\nu - g_{\mu\nu}) \not{q} - F_2^T q_\lambda (\gamma_\mu p_\nu - \gamma_\nu p_\mu) \not{q} - F_3^T q_\lambda (\gamma_\mu q_\nu - \gamma_\nu q_\mu) \not{q} \\ & + F_4^T q_\lambda (p_\nu q_\mu - p_\mu q_\nu) \not{q} - F_5^T (\gamma_\nu g_{\mu\lambda} - \gamma_\mu g_{\nu\lambda}) \not{q} \\ & + F_6^T (p_\nu g_{\mu\lambda} - p_\mu g_{\nu\lambda}) \not{q} + F_7^T (q_\nu g_{\mu\lambda} - q_\mu g_{\nu\lambda}) \not{q} + \cdots \Big] \gamma_5 u_Q^\lambda(p) \end{aligned} \tag{10}$$

where $m_{1/2}$ denotes the mass of the spin-1/2 baryon and $m_{3/2}$ denotes the mass of the spin-3/2 baryon. In the last line of the above equations, only the structures that have been used are written explicitly, and the three dots denote other structures.

2.2 Theoretical part of the correlation function

From eq. 5 it follows that for the calculation of the theoretical part of the correlation function, the expressions of the interpolating currents are needed. The interpolating current of the doubly heavy baryon is defined as:

$$j_{QQq}(x) = \sqrt{2} \varepsilon_{abc} \left[\left(Q^{aT}(x) C q^b(x) \right) \gamma_5 Q^c(x) + \beta \left(Q^{aT}(x) C \gamma_5 q^b(x) \right) Q^c(x) \right] \tag{11}$$

where Q denotes the heavy quark and q denotes the light quark. The matrix elements $\left\langle 0 \middle| q_{1\beta}(x) q_{2\eta}(0) Q_\lambda(0) \middle| B_Q^* \right\rangle$ in terms of the single heavy baryon distribution amplitudes are given as: (see [6] and [7])

$$\langle 0 | q_{1\alpha}(t_1 n) q_{2\beta}(t_2 n) Q_\gamma(0) | B_Q^* \rangle = \sum_i (\Gamma_i)_{\beta\alpha} A_\gamma^i(t_1, t_2) \tag{12}$$

where

$$\Gamma_1 = -\frac{1}{4} C \quad \Gamma_2 = -\frac{1}{4} \gamma_\mu C \quad \Gamma_3 = -\frac{1}{8} \sigma_{\mu\nu} C \quad \Gamma_4 = -\frac{1}{4} \gamma_\mu \gamma_5 C \tag{13}$$

$$\begin{aligned}
A^1 &= -\frac{1}{\sqrt{3}} f^{(2)} \psi_{\|}^{\mathbb{1}}(t_1,t_2)\bar{v}_\mu u_Q^\mu(v) \\
A^2 &= \frac{1}{\sqrt{3}} f^{(1)} \left[-\bar{v}_\nu \frac{v_+}{2} \psi_{\|}^{n}(t_1,t_2)\bar{n}_\mu + \psi_{\perp}^{\mathbb{1}}(t_1,t_2)\left(g_{\mu\nu} - \bar{v}_\mu \bar{v}_\nu\right) + \frac{\bar{v}_\nu}{2v_+} \psi_{\|}^{\bar{n}}(t_1,t_2) n_\mu \right] u_Q^\nu(v) \\
A^3 &= -\frac{i}{\sqrt{3}} f^{(2)} \left[-\left(v_+ \bar{n}_\nu \psi_{\perp}^{n}(t_1,t_2) + \frac{1}{v_+} n_\nu \psi_{\perp}^{\bar{n}}(t_1,t_2) \right)\left(g_{\mu\alpha} - \bar{v}_\mu \bar{v}_\alpha\right) - n_\mu \bar{n}_\nu \psi_{\|}^{n\bar{n}}(t_1,t_2)\bar{v}_\alpha \right] u_Q^\alpha(v) \\
A^4 &= -\frac{i}{2\sqrt{3}} f^{(1)} \epsilon^{\mu\nu\alpha\beta} n_\alpha \bar{n}_\beta \psi_{\perp}^{n\bar{n}}(t_1,t_2) u_Q^\nu(v)
\end{aligned} \tag{14}$$

Here, $u_Q^\nu(v)$ denotes the Rarita-Schwinger spinor of the spin-$3/2$ baryon with velocity v and n_α, $\bar{n}_\alpha$, and $\bar{v}_\alpha$ are defined as:

$$n_\alpha = \frac{1}{vx} x_\alpha \qquad \bar{n}_\alpha = 2v_\alpha - \frac{1}{vx} x_\alpha \qquad \bar{v}_\alpha = n_\alpha - v_\alpha, \tag{15}$$

3 Numerical analysis

In this section, we perform the numerical analysis of the form factors. Then, using the form factors, we will estimate the decay widths. The parameters entering the sum rules are the masses of the heavy quarks, the mass of the doubly heavy baryon and its residue, decay constants $f^{(1)}$ and $f^{(2)}$ of the single heavy baryon. For the masses of the heavy quarks, we used their values in the $\overline{MS}$ scheme, $\overline{m}_b(\overline{m}_b) = (4.18 \pm 0.03)$ GeV and $\overline{m}_c(\overline{m}_c) = (1.275 \pm 0.025)$ GeV [8], residues of the doubly heavy baryons are calculated in [5], and the masses can be found in [2] and[8] and the decay constants $f^{(1)}$ and $f^{(2)}$ can be found in[9]

The non-perturbative contribution to the light-cone sum rules comes from the distribution amplitudes (DA's) of the corresponding baryons. Forms of the DA's are given in [6]. [1]

In addition, we also have three parameters, namely the continuum threshold s_0, the Borel mass M^2, and the β parameter. To determine the working region of M^2, there are two requirements. M^2 should be large enough to ensure that the leading twist contribution is larger than the higher twist contributions, and it also should be small enough to suppress the higher states and continuum contributions. To examine the stability of the results with respect to Borel mass and the continuum threshold, we present the dependency of the results to M^2 with fixed values of β and s_0 and dependency of the results to $\cos(\theta)$ parameter where $\beta = \tan(\theta)$ with fixed values of M^2 and s_0 values in figure-1.

To extend the obtained results in the physical region of the q^2, which is $4m_\ell^2 \leq q^2 \leq (m_{1/2}^2 - m_{3/2}^2)$, we used the double pole parametrization.

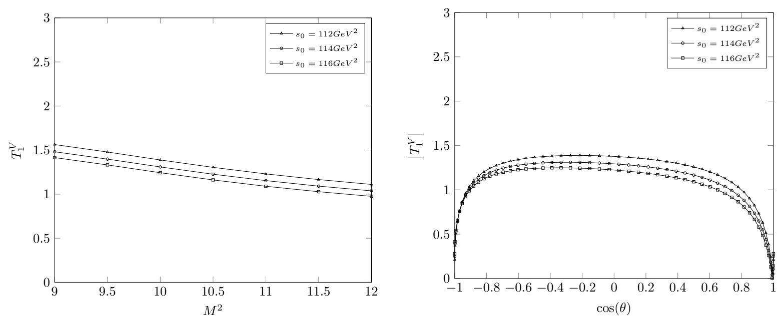
$$F_i(q^2) = \frac{F_i(0)}{1 - \dfrac{q^2}{m_i^2} + \alpha_i \left(\dfrac{q^2}{m_i^2}\right)^2} \tag{16}$$

Using the results of the form factors, we present the decay widths in the table below.

4 Conclusion

In this work, we presented the FCNC decay widths for the transitions of the spin-$1/2$ double heavy baryons to spin-$3/2$ single heavy baryons. We applied the light-cone sum rules method

[1] In [6], the authors expand the model functions in terms of Gegenbauer polynomials and chose $A = 1/2$ for the calculation of the model functions in the DA's. Since the value $A = 1/2$ causes some of the integral diverge, we simply excluded the last term in the Gegenbauer polynomial expansion.



(a) (b)

Figure 1. a) M^2 dependence of the T_1^V for $\Xi_{bb}^- \to \Sigma_b^{*-}$ transitions with different s_0 values where $\beta = 5$ **b)** $\cos(\theta)$ dependence of the $\left|T_1^V\right|$ for $\Xi_{bb}^- \to \Sigma_b^{*-}$ transitions for fixed $M^2(10\ \mathrm{GeV}^2)$ with different s_0 values where $\beta = \tan(\theta)$.

Table 1. Decay widths for the $B_{QQ} \to B_Q^* e^+ e^-$ transitions.

Transition	Γ / GeV	Γ / GeV [10]
$\Omega_{bb}^- \to \Omega_b^{*-} e^+ e^-$	1.94×10^{-19}	2.71×10^{-19}
$\Omega_{bb}^- \to \Xi_b^{*-} e^+ e^-$	9.35×10^{-21}	3.06×10^{-21}
$\Xi_{bb}^- \to \Sigma_b^{*-} e^+ e^-$	9.49×10^{-21}	6.52×10^{-21}
$\Xi_{bb}^- \to \Xi_b^{*-} e^+ e^-$	1.98×10^{-19}	1.43×10^{-19}
$\Xi_{bb}^0 \to \Sigma_b^{*0} e^+ e^-$	9.49×10^{-21}	3.27×10^{-21}
$\Xi_{bb}^0 \to \Xi_b^{*0} e^+ e^-$	1.98×10^{-19}	1.45×10^{-19}

to the FCNC decays of doubly heavy baryons and calculated the form factors. Using the form factors, we estimated the decay widths. Our predictions on the decay widths of the spin-1/2 double heavy baryon decays to the spin-3/2 single heavy baryon can be checked in further experiments in LHC.

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