

Vector meson dominance and radiative decays of heavy spin-3/2 baryons to heavy spin-1/2 baryons

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Abstract

Using the calculated values of the strong coupling constants of the heavy sextet spin-3/2 baryons to sextet and antitriplet heavy spin-1/2 baryons with light mesons within the light cone QCD sum rules method, and vector meson dominance assumption, the radiative decay widths are calculated. These widths are compared with the “direct” radiative decay widths predicted in the framework of the light cone QCD sum rules.

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Heavy baryons with a single heavy quark are quite promising for testing the predictions of the heavy symmetry and quark models (for a recent review see [1]). Last few years have been very successful on heavy baryon spectroscopy. Practically all $1/2^+$ and $3/2^+$ ground states with a single heavy quark have been discovered in the experiments [2].

With the operation of LHC, new possibility is opened for a comprehensive study of the properties of the heavy flavor hadrons as well as their electromagnetic, weak and strong decays [3]. The coupling constant of the heavy baryons with light mesons is the main ingredient for describing the strong decays. The strong coupling constants of the heavy sextet $3/2$ baryons B^* with the spin- $1/2$ sextet and antitriplet heavy baryons B with light vector mesons V within the light cone QCD sum rules (LCSR) are analyzed in [4].

In the present note we study the electromagnetic decays of heavy flavored hadrons assuming vector-meson dominance model (VDM) by using the results for the strong coupling constants of light vector mesons with heavy hadrons [4]. Important feature of these decays is also the fact that although electromagnetic interaction involves the constant of the fine structure α they are not suppressed by the phase space, as is the case for pion transitions. Moreover radiative decay for some $3/2$ baryons would be the main decay mode. The secondary aim of this note is to find an answer to the question how VDM works for transitions of heavy hadrons.

Let us start our discussion on the heavy baryon decays in the unitary symmetry. The $3/2 B^* \rightarrow 1/2 B$ electromagnetic baryon current in the unitary symmetry model with 5 flavors can be written as

$$J_{\mu}^{3/2 \rightarrow 1/2 \text{ el}} = \sum_{k=1}^5 e_k J_{\mu k}^k, \quad J_{\mu \delta}^{\tau} = \epsilon_{\beta\gamma\rho\delta\eta} \mathcal{O}_{\mu\nu} \bar{B}_{\alpha}^{\beta\gamma\eta} B^{*\nu \alpha\rho\tau}, \quad (1)$$

where $\mu, \nu=0,1,2,3$ are the Lorenz indices, and all other indices run from 1 to 5, and e_k means k 'th flavor electric charge $k = 1, 2, 3, 4, 5$ which is, naturally, to associate with the electric charge of the quarks u, d, s, c, b , correspondingly; and we do not specify the nature of $\mathcal{O}_{\mu\nu}$ for a moment.

The baryon $1/2^+$ wave function in terms of the quarks is

$$\sqrt{6} B_{\beta\gamma\tau\uparrow}^{\alpha} = \epsilon_{\beta\gamma\eta\rho\tau} \{q_{\uparrow}^{\alpha}, q_{\uparrow}^{\eta}\} q_{\downarrow}^{\rho}, \quad (2)$$

where $u = q^1, d = q^2, s = q^3, c = q^4, b = q^5$ (subscripts 1(2) or $\uparrow(\downarrow)$ mean spin up (down)).

Neglecting baryon currents related with heavy quarks Eq.(1) can be written as

$$J_{\mu}^{3/2 \rightarrow 1/2 \text{ el}} = \frac{1}{2}(e_u - e_d)(J_{\mu 1}^1 - J_{\mu 2}^2) + \frac{1}{2}(e_u + e_d)(J_{\mu 1}^1 + J_{\mu 2}^2) + e_s J_{\mu 3}^3, \quad (3)$$

The baryon currents have the same quantum numbers of ρ^0 , ω and ϕ mesons, respectively. It is easy now to express all the electromagnetic quantities through the VDM hypothesis in terms of the B^*BV couplings, where $V = \rho^0, \omega, \phi$.

Now we turn to the explicit forms of $\mathcal{O}_{\mu\nu}$. Using the gauge invariance the amplitude $B^* \rightarrow B\gamma$ is parametrized in terms of form factors as follows [5]:

$$\begin{aligned} \langle B_Q(p)\gamma(q)|B^*(p+q) \rangle = & \bar{u}(p) \left\{ g_1 (q_{\mu} \not{\epsilon} - \epsilon_{\mu} \not{q}) + g_2 [(P\epsilon) q_{\mu} - (Pq) \epsilon_{\mu}] \right. \\ & \left. + g_3^V [(q\epsilon) q_{\mu} - q^2 \epsilon_{\mu}] \right\} \gamma_5 u^{\mu}(p+q), \end{aligned} \quad (4)$$

where u^μ is the Rarita Schwinger spinor, ε_μ is the photon polarization 4-vector, q_μ is its momentum, p being momentum of the 1/2 baryon and $P = 2p + q$. Obviously for real photons last term in the Eq.(4) is equal to zero.

The VDM implies that $B^*B\gamma$ vertex can be obtained from B^*BV vertex by converting vector meson V to photon, i.e., $B^*BV \rightarrow B^*B\gamma$. The corresponding strong B^*BV vertex is parametrized in terms of the form factors similar to the $B^*B\gamma$ vertex [6]:

$$\begin{aligned} \langle B_Q(p)V(q)|B^*(p+q)\rangle &= \bar{u}(p)\{g_1^V(q_\mu\not{q}^V - \eta_\mu\not{q}) + g_2^V[(P\eta^V)q_\mu - (Pq)\eta_\mu^V] \\ &+ g_3^V[(q\eta^V)q_\mu - q^2\eta_\mu^V]\}\gamma_5 u^\mu(p+q), \end{aligned} \quad (5)$$

where now η_μ^V is the vector polarization of light vector meson with the momentum q_μ . We disregard the form factor g_3 as it corresponds to longitudinal polarization not presented in photon. In this chain it is necessary to go from $q^2 = m_V^2$ to $q^2 = 0$ and make the replacement,

$$\eta_\mu^V = \frac{e}{g_V} e_\mu. \quad (6)$$

Obviously, when $e_\mu \rightarrow q_\mu$, the $B^*B\gamma$ amplitude should vanish as is required by the gauge invariance.

Putting Eq. (6) in Eq.(5), we get

$$\begin{aligned} \langle B_Q(p)\gamma(q)|B^*(p+q)\rangle &= \sum_{V=\rho,\omega,\phi} \frac{e}{g_V} \bar{u}(p)\{g_1^V(q_\mu\not{q} - \varepsilon_\mu\not{q}) \\ &+ g_2^V[(P\varepsilon)q_\mu - (Pq)\varepsilon_\mu]\}\gamma_5 u^\mu(p+q). \end{aligned} \quad (7)$$

Comparing Eqs. (7) and (4), we obtain the usual relation among the form factors of B^*BV and $B^*B\gamma$ vertices,

$$g_i = \sum_{V=\rho,\omega,\phi} g_i^V \frac{1}{g_V}.$$

It should be noted here that we neglect the possible contributions coming from J/Ψ and Υ mesons, since B^*BV vertex is proportional to $m_{J/\Psi,(\Upsilon)}^{-3/2}$ in the heavy quark limit (This is not a general rule, as for example in quark model approach charm quark contribution is taken comparable with that of strange quark [7]). In numerical analysis we use the experimental values $g_\rho = 5.05$, $g_\omega = 17.02$ and $g_\phi = -12.89$ [2].

From experimental point of view multipole form factors are much more suitable than the form factors g_1 and g_2 themselves. In our case the multipole form factors are the magnetic dipole G_M and electric quadrupole G_E form factors. Relations among G_M , G_E and g_1 and g_2 at $q^2 = 0$ can be found in [6], whose forms are as follows:

$$\begin{aligned} G_M &= (3m_{B^*} + m_B) \frac{m_B}{3m_{B^*}} g_1 + (m_{B^*} - m_B) m_B \frac{g_2}{3}, \\ G_E &= (m_{B^*} - m_B) \frac{m_B}{3m_{B^*}^*} (g_1 + m_{B^*}^* g_2). \end{aligned} \quad (8)$$

Using these relations it is straightforward to get the width of the radiative decay $B_Q^* \rightarrow B_Q\gamma$, which can be written as:

$$\Gamma_{B_Q^* \rightarrow B_Q\gamma} = \frac{3\alpha}{4} \frac{k_\gamma^3}{m_{B_Q}^2} (3G_E^2 + G_M^2), \quad k_\gamma = \frac{m_{B^*}^2 - m_B^2}{2m_{B^*}}.$$

Now we implement the VDM hypothesis through the Eq.(6) into the LCSR and calculate the G_M 's and G_E 's. The results of our calculations we put into the tables together with the results of some previous works.

We expect that similar to the case of the decuplet–octet radiative decays G_E 's are suppressed in comparison with G_M 's. Indeed, this is confirmed by explicit calculations. First let us try to understand the possible tendency of the VDM calculations together with the QCD results on the examples of measured quantities, $\Gamma(\Delta^+ \rightarrow p\gamma) = 660 \pm 50 \text{ keV}$ [2] and $\Gamma(\Sigma^{*0} \rightarrow \Lambda\gamma) = 445 \pm 80 \text{ keV}$ [8]. Both decays in VDM can proceed only through $\rho \rightarrow \gamma$ conversion. So we take $g_1^{\Delta^+ \rightarrow p\rho^0} = \sqrt{2}g_1^{\Delta^0 \rightarrow p\rho^-} = \sqrt{2}(9.1 \pm 2.9)$ and $g_1^{\Sigma^{*0} \rightarrow \Lambda\rho^0} = g_1^{\Sigma^{*-} \rightarrow \Lambda\rho^-} = -10 \pm 3$ from the Table II of [9]. With $g_\rho = 5.05$ we get $g_1^{VDM}(\Delta^+ \rightarrow p\gamma) = 2.26$, where from $G_M^{VDM}(\Delta^+ \rightarrow p\gamma) \sim 1.18g_1 = 2.51$ and $\Gamma^{VDM}(\Delta^+ \rightarrow p\gamma) = 860 \text{ keV}$ while $g_1^{VDM}(\Sigma^{*0} \rightarrow \Lambda\gamma) = 2.0$ and $\Gamma^{VDM}(\Sigma^{*0} \rightarrow \Lambda\gamma) = 590 \text{ keV}$. So for these decays VDM combined with the QCD sum rules has the tendency to oversize data by a factor 1.5–2.0.

Keeping this in mind we return now to heavy baryons decays. In Table 1 we present the values of the magnetic dipole G_M and the electric quadrupole form factors at $q^2 = 0$, which are obtained within VDM. In this Table, for a comparison, we also present the values of these form factors as calculated from direct $B_{Q^*} \rightarrow B\gamma$ decay in the framework of LCSR [6]. The radiative decays of the heavy sextet spin–3/2 baryons to the sextet and antitriplet spin–1/2 heavy baryons are calculated in this work using the most general form of the interpolating current without using VDM hypothesis.

Using the values of the couplings G_M and G_E presented in Table 1 and Eq. (8), we calculate the widths of the radiative decays whose values are presented in Table 2.

In Table 2 we also present the predictions of the works [10],[11] on radiative decays, where VDM hypothesis has been used in estimating radiative decays of the heavy spin–1/2 baryons in the framework of the LCSR approach with the Ioffe interpolating current, as well as results of several preceding works on a subject [12]–[16].

It follows from Table 2 that, there are considerable differences between the VDM predictions and the direct radiative decay ones [6], for all channels. This difference can be explained as follows. The decay width is very sensitive to the mass difference of the heavy flavored baryons B^* and B . If the mass of one of the baryons changes even at milli–digit level, the decay width can change several times. The baryon masses are taken from PDG, while in [6] for the masses the mass sum rules were used. This is the cause of the large difference in the predictions for the widths, while there is rather a reasonable agreement for the values of $G_{M,E}$.

Our results are also different from those predicted in [10, 11], where VDM has also been used. This discrepancy in the results is mainly due to the difference of the values of the residues of spin–1/2 heavy baryons, as well as to the different masses used for the heavy baryons.

In conclusion, we estimate the widths of radiative decays of the heavy spin–3/2 baryons to spin–1/2 heavy baryons using the values of strong coupling constants for the $B_Q^* B_Q V$

vertices where V is a light vector meson, and VDM. It is found that VDM works reasonably well for the heavy-baryon systems. The obtained results on the radiative widths are compared with the direct calculation of these decay widths as is predicted by LCSR method.

Channel	G_E VDM	G_M VDM	G_E [6]	G_M [6]	G_M^* [10], [11]
$\Xi_b^{*0} \rightarrow \Xi_b^0 \gamma$	0.017	2.93	—	—	3.24
$\Xi_b^{*-} \rightarrow \Xi_b^{\prime-} \gamma$	-0.021	-4.63	—	—	-3.86
$\Sigma_b^{*+} \rightarrow \Sigma_b^+ \gamma$	0.016	8.35	0.026	4.2	8.85
$\Sigma_b^{*0} \rightarrow \Sigma_b^0 \gamma$	0.003	1.73	0.005	1.0	2.22
$\Sigma_b^{*-} \rightarrow \Sigma_b^- \gamma$	-0.009	-4.53	-0.016	-2.1	4.42
$\Sigma_b^{*0} \rightarrow \Lambda_b^0 \gamma$	0.164	11.8	0.075	7.3	—
$\Xi_b^{*0} \rightarrow \Xi_b^0 \gamma$	-0.185	-12.01	-0.085	-8.5	—
$\Xi_b^{*-} \rightarrow \Xi_b^- \gamma$	-0.025	-1.09	-0.011	-0.9	—
$\Omega_b^{*-} \rightarrow \Omega_b^- \gamma$	-0.034	-4.52	—	—	—
$\Xi_c^{*+} \rightarrow \Xi_c^+ \gamma$	0.019	1.33	—	—	1.86
$\Xi_c^{*0} \rightarrow \Xi_c^0 \gamma$	-0.026	-2.20	—	—	2.22
$\Sigma_c^{*++} \rightarrow \Sigma_c^{++} \gamma$	0.037	3.68	0.030	2.8	5.22
$\Sigma_c^{*+} \rightarrow \Sigma_c^+ \gamma$	0.009	0.84	-0.003	0.5	1.31
$\Sigma_c^{*0} \rightarrow \Sigma_c^0 \gamma$	-0.020	-2.00	0.014	1.2	2.60
$\Sigma_c^{*+} \rightarrow \Lambda_c^+ \gamma$	0.192	5.70	0.060	3.8	—
$\Xi_c^{*+} \rightarrow \Xi_c^+ \gamma$	-0.147	-5.91	-0.075	-4.0	—
$\Xi_c^{*0} \rightarrow \Xi_c^0 \gamma$	-0.013	-0.55	-0.007	-0.45	—
$\Omega_c^{*0} \rightarrow \Omega_c^0 \gamma$	-0.026	-2.17	—	—	2.14

Table 1: The values of the electric quadrupole G_E and the magnetic dipole G_M form factors at $q^2 = 0$. G_M^* are calculated from g_1 's of [10],[11] neglecting g_2 's.

Channel	Γ (keV) VDM	Γ (keV) [6]	Γ (keV) [10], [11]	Γ (keV)
$\Xi_b^{*0} \rightarrow \Xi_b^{\prime 0} \gamma$	0.281	—	0.047	—
$\Xi_b^{*-} \rightarrow \Xi_b^{\prime -} \gamma$	0.702	—	0.066	—
$\Sigma_b^{*+} \rightarrow \Sigma_b^+ \gamma$	0.137	0.46	0.12	0.080[15]
$\Sigma_b^{*0} \rightarrow \Sigma_b^0 \gamma$	0.006	0.028	0.0076	0.005[15]
$\Sigma_b^{*-} \rightarrow \Sigma_b^- \gamma$	0.040	0.11	0.03	0.020[15]
$\Sigma_b^{*0} \rightarrow \Lambda_b^0 \gamma$	221.5	114.0	—	260.0[15]
$\Xi_b^{*0} \rightarrow \Xi_b^0 \gamma$	270.8	135.0	—	—
$\Xi_b^{*-} \rightarrow \Xi_b^- \gamma$	2.246	1.5	—	—
$\Omega_b^{*-} \rightarrow \Omega_b^- \gamma$	2.873	—	0.00074	—
$\Xi_c^{*+} \rightarrow \Xi_c^+ \gamma$	0.485	—	0.96	—
$\Xi_c^{*0} \rightarrow \Xi_c^{\prime 0} \gamma$	1.317	—	0.12	—
$\Sigma_c^{*++} \rightarrow \Sigma_c^{++} \gamma$	3.567	2.65	6.36	1.70[12], 1.15[7] 3.04[16]
$\Sigma_c^{*+} \rightarrow \Sigma_c^+ \gamma$	0.187	0.08	0.40	0.01[12], 0.00006[7] 0.19[16], 0.14[13]
$\Sigma_c^{*0} \rightarrow \Sigma_c^0 \gamma$	1.049	0.40	1.58	1.20[12], 1.12[7]
$\Sigma_c^{*+} \rightarrow \Lambda_c^+ \gamma$	409.3	130.0	—	250.0[12], 154.48[7] 151.0[13], 230.0[14]
$\Xi_c^{*+} \rightarrow \Xi_c^+ \gamma$	152.4	52.0	—	124.0[12], 63.32[7] 75.60[14]
$\Xi_c^{*0} \rightarrow \Xi_c^0 \gamma$	1.318	0.66	—	0.80[12], 0.30[7] 0.90[14]
$\Omega_c^{*0} \rightarrow \Omega_c^0 \gamma$	1.439	—	1.16	0.36[12], 2.02[7]

Table 2: Widths of the radiative decays of heavy flavored baryons.

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