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Two body nonleptonic decays of Λ_b involving proton

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Abstract. We study some nonleptonic decays of Λ_b-baryon involving transition of a heavy to light quark, using nonrelativistic quark model for form factors. The decay rates for two such decays are consistent with the data available. Also these decays can give us information on the CKM matrix element $|V_{ub}|$.

Keywords. Nonleptonic decays; nonrelativistic quark model.

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1. Introduction

Nonleptonic weak decays of hadrons are complicated to study as compared to semileptonic decays. It is because of the strong interaction effects involved in the former. As these strong interaction effects are smaller at higher energy scales, it is expected that the study of nonleptonic decays of heavy hadrons will help in the understanding of QCD effects and hence, of the nonleptonic decay processes, in general. Progress has been made in the study of charmed baryon decays both experimentally [1–3] and theoretically [4–6]. On the other hand, a meagre data are available in the case of b-baryon decays [1]. It is interesting to learn that the first successful measurement of exclusive hadronic decay rate of bottom baryons i.e. $\Lambda_b \to \Lambda J/\psi$, [7] has been made and needless to say, more and more data of bottom baryon decays will become available in the coming few years.

Encouraged by the measurement of the branching ratio of the decay $\Lambda_b \to \Lambda J/\psi$ and the upper limits on the decay rates of decay processes $\Lambda_b \to p\pi$ and $\Lambda_b \to pK$ [1], we have studied some two body nonleptonic decay modes of Λ_b-baryon. Moreover, these decays involving heavy to light quark transition, can help us in determining the CKM matrix element $|V_{ub}|$.

The factorization approximation works well in heavy to heavy transitions [8]. It has also been used in the case of heavy to light transitions [9]. Following them, we have also used the factorization ansatz in our calculations. To evaluate the form factors, the nonrelativistic quark model (NQRM) with $1/m_Q$ corrections [10], which is in good agreement with HQET, has been employed.

The paper is organized as follows. In §2, we present the formulae for the calculation of decay rates, while in §3, we present our results and conclusions.

2. Formalism

The general amplitudes for the decays $B_{\mathrm{b}}(1/2^+) \to B(1/2^+) + P(V)$ can be written as:

$$M\left[B_{\mathrm{i}}\left(\frac{1^+}{2}\right) \to B_{\mathrm{f}}\left(\frac{1^+}{2}\right) + P\right] = i\bar{u}_{\mathrm{f}}(p_{\mathrm{f}})(A + B\gamma_5)u_{\mathrm{i}}(p_{\mathrm{i}}) \tag{1}$$

and

$$M\left[B_{\mathrm{i}}\left(\frac{1^+}{2}\right) \to B_{\mathrm{f}}\left(\frac{1^+}{2}\right) + V\right] = \bar{u}_{\mathrm{f}}(p_{\mathrm{f}})\epsilon^{*\mu}[A_1\gamma_\mu\gamma_5 + A_2(p_{\mathrm{f}})_\mu\gamma_5 + B_1\gamma_\mu + B_2(p_{\mathrm{f}})_\mu]u_{\mathrm{i}}(p_{\mathrm{i}}) \tag{2}$$

where ϵ_μ is the polarization vector of the vector meson with

$$A = \lambda a_{1,2} f_{\mathrm{P}}(m_{\mathrm{i}} - m_{\mathrm{f}}) f_1(m_{\mathrm{P}}^2), \tag{3}$$

$$B = \lambda a_{1,2} f_{\mathrm{P}}(m_{\mathrm{i}} + m_{\mathrm{f}}) g_1(m_{\mathrm{P}}^2) \tag{4}$$

and

$$A_1 = -\lambda a_{1,2} f_{\mathrm{V}} m_{\mathrm{V}}[g_1(m_{\mathrm{V}}^2) + g_2(m_{\mathrm{V}}^2)(m_{\mathrm{i}} - m_{\mathrm{f}})], \tag{5}$$

$$A_2 = -2\lambda a_{1,2} f_{\mathrm{V}} m_{\mathrm{V}} g_2(m_{\mathrm{V}}^2), \tag{6}$$

$$B_1 = \lambda a_{1,2} f_{\mathrm{V}} m_{\mathrm{V}}[f_1(m_{\mathrm{V}}^2) - f_2(m_{\mathrm{V}}^2)(m_{\mathrm{i}} + m_{\mathrm{f}})], \tag{7}$$

$$B_2 = 2\lambda a_{1,2} f_{\mathrm{V}} m_{\mathrm{V}} f_2(m_{\mathrm{V}}^2). \tag{8}$$

Also $\lambda = G_F V_{\mathrm{ub}} V_{qq'}/\sqrt{2}$, with $(qq') = (ud), (cs), (us)$ or (cd) depending on the final meson state under consideration, f_{i} and g_{i} are the form factors defined by

$$\langle B_{\mathrm{f}}(p_{\mathrm{f}})|V_\mu - A_\mu|B_{\mathrm{i}}(p_{\mathrm{i}})\rangle = \bar{u}_{\mathrm{f}}(p_{\mathrm{f}})\left\{f_1(q^2)\gamma_\mu + if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu - [g_1(q^2)\gamma_\mu + ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu]\gamma_5\right\} u_{\mathrm{i}}(p_{\mathrm{i}}), \tag{9}$$

$m_{\mathrm{i}}(m_{\mathrm{f}})$ is the mass of the initial(final) baryon, f_{P} and f_{V} are the decay constants of pseudoscalar and vector mesons, respectively, defined by

$$\langle 0|A_\mu|P\rangle = if_{\mathrm{P}}q_\mu, \tag{10}$$

$$\langle 0|V_\mu|V\rangle = f_{\mathrm{V}} m_{\mathrm{V}} \epsilon_\mu^*, \tag{11}$$

a_1, a_2 are the Wilson coefficients whose values [11] we take to be $a_1 \approx 1$ and $a_2 \simeq 0.23$.

The form factors f_i and g_i defined above are calculated using the nonrelativistic quark model framework proposed by Cheng and Tseng [10] at maximum q^2 and are given by,

$$\begin{aligned}
f_1(q_m^2)/N_{fi} &= 1 - \frac{\Delta m}{2m_i} + \frac{\Delta m}{4m_i m_q}\left(1 - \frac{\bar{\Lambda}}{2m_f}\right)(m_i + m_f - \eta\Delta m) \\
&\quad - \frac{\Delta m}{8m_i m_f}\frac{\bar{\Lambda}}{m_Q}(m_i + m_f + \eta\Delta m), \\
f_2(q_m^2)/N_{fi} &= \frac{1}{2m_i} + \frac{1}{4m_i m_q}\left(1 - \frac{\bar{\Lambda}}{2m_f}\right)[\Delta m - (m_i + m_f)\eta] \\
&\quad - \frac{\bar{\Lambda}}{8m_i m_f m_Q}[\Delta m + (m_i + m_f)\eta], \\
f_3(q_m^2)/N_{fi} &= \frac{1}{2m_i} - \frac{1}{4m_i m_q}\left(1 - \frac{\bar{\Lambda}}{2m_f}\right)(m_i + m_f - \eta\Delta m) \\
&\quad + \frac{\bar{\Lambda}}{8m_i m_f m_Q}(m_i + m_f + \eta\Delta m), \\
g_1(q_m^2)/N_{fi} &= \eta + \frac{\Delta m\bar{\Lambda}}{4}\left(\frac{1}{m_i m_q} - \frac{1}{m_f m_Q}\right)\eta, \\
g_2(q_m^2)/N_{fi} &= -\frac{\bar{\Lambda}}{4}\left(\frac{1}{m_i m_q} - \frac{1}{m_f m_Q}\right)\eta, \\
g_3(q_m^2)/N_{fi} &= -\frac{\bar{\Lambda}}{4}\left(\frac{1}{m_i m_q} + \frac{1}{m_f m_Q}\right)\eta
\end{aligned} \tag{12}$$

where $\bar{\Lambda} = m_f - m_q$, $q_m^2 = (\Delta m)^2$ with $\Delta m = m_i - m_f$, is the maximum momentum (q^2) transfer. Also, $\eta = N'_{fi}/N_{fi}$ and is one for antitriplet baryon and $-1/3$ for sextet baryon. N_{fi} and N'_{fi} are the flavor factors,

$$\begin{aligned}
N_{fi} &= {}_{\text{flavor-spin}}\langle B_f|b_q^+ b_Q|B_i\rangle_{\text{flavor-spin}} \\
N'_{fi} &= {}_{\text{flavor-spin}}\langle B_f|b_q^+ \sigma_z^Q b_Q|B_i\rangle_{\text{flavor-spin}}
\end{aligned} \tag{13}$$

for the heavy quark Q in the parent baryon B_i transiting into the light quark q in the daughter baryon B_f. m_Q and m_q denote the masses of these heavy and light quarks respectively. The light diquark present in the parent baryon behaves as a spectator. For the q^2 dependence of the baryonic form factors, we will use the pole dominance of the form,

$$f(q^2) = \frac{f(0)}{(1 - (q^2/m_V^2)^n} \tag{14}$$

and

$$g(q^2) = \frac{g(0)}{(1 - (q^2/m_A^2)^n}. \tag{15}$$

Here, m_V and m_A denote, respectively, the pole masses of the vector meson and axial-vector meson having the quantum numbers of the current involved and generally $n = 2$, for the case of baryons.

With the amplitude (1) for $(1^+/2) \to (1^+/2) + P$ decay, the decay rate is given by,

$$\Gamma\left(\frac{1^+}{2} \to \frac{1^+}{2} + P\right) = \frac{p_c}{8\pi}\left[\frac{(m_i + m_f)^2 - m_P^2}{m_i^2}|A|^2 + \frac{(m_i - m_f)^2 - m_P^2}{m_i^2}|B|^2\right], \tag{16}$$

and for $1^+/2 \to 1^+/2 + V$ decay, using (2), we have [4],

$$\Gamma\left(\frac{1^+}{2} \to \frac{1^+}{2} + V\right) = \frac{p_c}{8\pi}\frac{E_f + m_f}{m_i}\left[2(|S|^2 + |P_2|^2) + \frac{E_V^2}{m_V^2}(|S + D|^2 + |P_1|^2)\right] \tag{17}$$

with

$$S = -A_1$$
$$P_1 = -\frac{p_c}{E_V}\left(\frac{m_i + m_f}{E_f + m_f}B_1 + m_i B_2\right),$$
$$P_2 = \frac{p_c}{E_f + m_f}B_1,$$
$$D = -\frac{p_c^2}{E_V(E_f + m_f)}(A_1 - m_i A_2), \tag{18}$$

where p_c is the c.m. momentum.

3. Results and conclusion

The values of the decay constants [12] involved are listed in table 1, whereas table 2 contains the numerical values of different decay rates and branching ratios calculated by using (16) and (17) respectively for the decays $\Lambda_b \to pP$ and $\Lambda_b \to pV$. To evaluate the branching ratios, we have used $\tau_{\Lambda_b} = 1.24 \times 10^{-12}$ s [1].

The branching ratios for two of the decays viz. $\Lambda_b \to p\pi$ and $\Lambda_b \to pK$ are consistent with the data available [1], as is clear from table 2.

Table 1. The decay constants in MeV.

Meson	Decay constant	Meson	Decay constant
π	132	ρ	216
K	162	K^*	221
D	200	D^*	230
D_s	241	D_s^*	270

Table 2. Branching ratios for various decays.

Decay	Theoretical value	Experimental value
$\Lambda_b \to p\pi$	0.71×10^{-5}	$< 5 \times 10^{-5}$
$\Lambda_b \to pD_s$	0.30×10^{-4}	
$\Lambda_b \to pK$	0.54×10^{-6}	$< 5 \times 10^{-5}$
$\Lambda_b \to pD$	1.04×10^{-6}	
$\Lambda_b \to p\rho$	1.01×10^{-5}	
$\Lambda_b \to pD_s^*$	0.55×10^{-4}	
$\Lambda_b \to pK^*$	0.59×10^{-6}	
$\Lambda_b \to pD^*$	1.75×10^{-6}	

The decays involving heavy to light i.e. $b \to u$ transition can give us information on the CKM matrix element $|V_{ub}|$. If we take the ratio of the decay width $\Gamma(\Lambda_b \to p\pi)$ to $\Gamma(\Lambda_c \to \Lambda\pi)$ [3] or of $\Gamma(\Lambda_b \to pD_s)$ to $\Gamma(\Lambda_b \to \Lambda_c D_s)$ [13], then the ratio comes out to be proportional to $|V_{ub}|/|V_{cs}|$ and from where we can estimate the value of $|V_{ub}|$.

To conclude, we have studied some nonleptonic decays of Λ_b baryon involving $b \to u$ transition based on NQRM form factors including $1/m_Q$ corrections. These decays provide us an easier way to evaluate the CKM matrix element $|V_{ub}|$, if we are able to measure their decay rates.

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