The decay $\Lambda_b \to \Lambda_c + \rho^-$

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Using the heavy-quark approximation and factorization, it is shown that $\Lambda_b \to \Lambda_c + \rho^-$ has a branching ratio 60% that of $\Lambda_b \to \Lambda_c + \pi^-$ and an asymmetry parameter α of −0.9.

In the near future, a large sample of Λ_b baryons should be available at the CERN e^+e^- collider LEP and other machines. Using the heavy-quark approximation,[1] the form factors for the semileptonic decay $\Lambda_b \to \Lambda_c\, e^-\bar{\nu}_e$ have been predicted.[2] In this Brief Report, we consider the decay mode $\Lambda_b \to \Lambda_c \rho^-$ in the same approximation with the additional assumption of factorization.[3]

The effective Hamiltonian, including short distance QCD corrections, for decays of b-flavored hadrons into charmed, nonstrange states in the standard model is given by[4,5]

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} U_{bc}U_{ud}(f_c \bar{c}_L \gamma_\mu b_L\, \bar{d}_L \gamma_\mu\, u_L + f_d \bar{d}_L \gamma_\mu b_L \bar{c}_L \gamma_\mu u_L), \tag{1}$$

where $f_c = \frac{1}{3}\,(2f_+ + f_-)$, $f_d = \frac{1}{3}\,(2f_+ - f_-)$, $f_- = [\alpha_s(\mu)/\alpha_s(M_W)]^\beta$, $f_+ = (f_-)^{-1/2}$, $\beta = \frac{12}{23}$ and μ is between m_c and m_b. For a decay mode such as $\Lambda_b \to \Lambda_c + \rho^-$ where the amplitude is assumed to be factorizable, only the first term contributes with the coefficient f_c in the range 1–1.1.[4,5] In the factorized form, the amplitude for $\Lambda_b \to \Lambda_c + \rho^-$ is given by

$$\frac{G_F}{\sqrt{2}}\, U_{bc}\, U_{ud}\, f_c \langle \Lambda_c \mid \bar{c}\, \gamma_\mu\, (1+\gamma_5)\, b \mid \Lambda_b \rangle \langle \rho \mid \bar{d}\, \gamma_\mu (1+\gamma_5)\, u \mid 0 \rangle. \tag{2}$$

The matrix element $\langle \rho \mid \bar{d}\, \gamma_\mu\, (1+\gamma_5)\, u \mid 0 \rangle$ is $f_\rho\, \epsilon_\mu(q)$, where $f_\rho \approx 0.11$ GeV^2, and $\epsilon_\mu(q)$ is the polarization vector for a ρ of momentum q. The baryonic matrix element, in the heavy-quark limit has been evaluated[2] and is given by

$$\langle \Lambda_c \mid \bar{c}\, \gamma_\mu (1+\gamma_5)\, b \mid \Lambda_b \rangle = F \bar{u}_{\Lambda_c}\, \gamma_\mu\, (1+\gamma_5) u_{\Lambda_b}, \tag{3}$$

where the single form factor F is given by

$$F = \left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{a_I} \left(\frac{\alpha_s(m_c)}{\alpha_s(\mu)}\right)^{a_L} \eta(v\cdot v'), \tag{4}$$

where $a_I = -6/25$, $a_L = 8[v\cdot v' r(v\cdot v') - 1]/27$, with

$$r(v\cdot v') = \frac{1}{\sqrt{(v\cdot v')^2 - 1}} \ln[v\cdot v' + \sqrt{(v\cdot v')^2-1}]$$

and v and v' are the four-velocities of the b and c quarks. The function $\eta(v\cdot v')$ is the universal, nonperturbative Isgur-Wise function, normalized to 1 at $v\cdot v' = 1$. The relation of $v\cdot v'$ to the four-momentum transfer squared q^2 is

$$v\cdot v' = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c}}. \tag{5}$$

For example, for $\Lambda_b \to \Lambda_c + \rho^-$, $q^2 = m_\rho^2$ and for a Λ_b mass of 5.7 GeV, $v\cdot v' = 1.42$ and for $\Lambda_b \to \Lambda_c + \pi^-$, $v\cdot v' = 1.45$. For the ρ decay mode, $F_\rho \cong 1.066\, \eta(1.42)$, and for the π decay mode, $F_\pi \cong 1.06\eta(1.45)$.

With this baryonic matrix element for (3), the matrix element for the decay $\Lambda_b \to \Lambda_c + \rho^-$ becomes

$$\frac{G_F}{\sqrt{2}} U_{bc} U_{ud} f_\rho f_c F \bar{u}_{\Lambda_c} \gamma_\mu (1+\gamma_5) u_{\Lambda_b} \epsilon_\mu. \tag{6}$$

Comparing this to the general form[6] in the rest frame of Λ_b,

$$\chi^\dagger_{\Lambda_c} [S\boldsymbol{\sigma} + P_1 \mathbf{p} + iP_2(\mathbf{p}\times\boldsymbol{\sigma}) + D(\boldsymbol{\sigma}\cdot\mathbf{p})\mathbf{p}]\cdot\, \boldsymbol{\epsilon}\chi_{\Lambda_b} \tag{7}$$

(with $\mathbf{p}$ now a unit vector in the direction of outgoing baryon[7]), we can read off the values for the four amplitudes S, P_1, P_2, and D as

$$S = \frac{1}{\sqrt{2}} G_F U_{bc} U_{ud} f_\rho f_c F, \tag{8}$$

$$P_1/S = -\left(\frac{m_{\Lambda_b} + m_{\Lambda_c}}{E_{\Lambda_c} + m_{\Lambda_c}}\right)\left(\frac{p}{E_\rho}\right) \approx -1.368, \tag{9}$$

$$P_2/S = p/(E_{\Lambda_c} + m_{\Lambda_c}) \approx 0.42, \tag{10}$$

$$D/S = p^2/E\rho(E_{\Lambda_c} + m_{\Lambda_c}) \approx 0.4. \tag{11}$$

From these expressions, the asymmetries and the decay rate can be read off. The up-down asymmetry α of the final Λ_c with respect to Λ_b polarization is

$$A(\text{up-down}) = 1 + \alpha \mathbf{p} \cdot \hat{\mathbf{n}}_{\Lambda_b}, \tag{12}$$

where

$$\alpha = 2\text{Re}\frac{[(1+D/S)^* P_1/S + 2(P_2^*/S)m_\rho^2/E_\rho^2]}{K} \tag{13}$$

and

$$K = [\,|1 + D/S|^2 + |P_1/S|^2 + 2(1+|P_2/S|^2)m_\rho^2/E_\rho^2]. \tag{14}$$

We find $\alpha \approx -0.9$, a reflection of the $V-A$ structure of the matrix elements. There are other asymmetry parameters defined by the polarization of the final Λ_c:

$$A(\mathbf{N}_{\Lambda_c}) = d\Omega\,[1 + \alpha \mathbf{p}\cdot \mathbf{n}_{\Lambda_b}]\,[1 + \mathbf{n}_{\Lambda c}\cdot \mathbf{N}] \tag{15}$$

$$\mathbf{N} = \frac{(\alpha' + \gamma' \mathbf{p}\cdot \mathbf{n}_{\Lambda_b})\mathbf{p} + \beta \mathbf{p}\times \mathbf{n}_{\Lambda_b} + \gamma(\mathbf{p}\times[\mathbf{p}\times \mathbf{n}_{\Lambda_b})]}{1+\alpha \mathbf{p}\cdot \mathbf{n}_{\Lambda_b}} \tag{16}$$

Using the expressions for α', γ, γ' given elsewhere,[6,7] we find $\alpha' \approx -1$, $\gamma \approx 0.02$ and $\gamma' \approx 0.88$.

The total decay rate is given by[6,7]

$$\Gamma = \frac{1}{8\pi}\left(\frac{E_{\Lambda_c} + m_{\Lambda_c}}{m_{\Lambda_b}}\right) p_\rho\, K\,(E\rho^2/m_\rho^2)\,|S|^2, \tag{17}$$

which can be written as

$$\Gamma(\Lambda_b \to \Lambda_c \rho^-) = \left(\frac{G_F^2\,|U_{cb}|^2\,\Sigma^3\Delta^3\,|f_c|^2|F_\rho|^2}{16\pi\, m_{\Lambda_b}^3}\right) \times \frac{\Sigma^2}{(2m_{\Lambda_b})^2}\frac{f_\rho^2}{4m_\rho^2}\,K, \tag{18}$$

where $\Sigma = m_{\Lambda_b} + m_{\Lambda_c}$ and $\Delta = m_{\Lambda_b} - m_{\Lambda_c}$ and corrections of order m_ρ^2/E_ρ^2 are neglected. The decay rate for $\Lambda_b \to \Lambda_c\, \pi^-$ in the same approximation is[4]

$$\Gamma(\Lambda_b \to \Lambda_c \pi^-) = \left(\frac{G_F^2\,|U_{cb}|^2\,\Sigma^3\Delta^3\,|f_c|^2|F_\pi|^2}{16\pi m_{\Lambda_b}^3}\right) f_\pi^2. \tag{19}$$

If we assume that the form factor F for ρ and π are nearly equal [this amounts to just assuming $\eta(1.45) \approx \eta(1.42)$], then we have that

$$\frac{\Gamma\,(\Lambda_b \to \Lambda_c + \rho^-)}{\Gamma\,(\Lambda_b \to \Lambda_c + \pi^-)} = \left(\frac{\Sigma}{2m_{\Lambda_b}}\right)^2 \left(\frac{f_\rho}{2f_\pi\, m_\rho}\right)^2 K \approx 0.6. \tag{20}$$

We predict $\Lambda_c\, \rho^-$ mode at 60% of $\Lambda_c\, \pi^-$ mode for Λ_b decay.

If the absolute value of the function η is known, the individual decay rates can be calculated. For this one has to await the measurement of the form factor in $\Lambda_b \to \Lambda_c\, e^-\, \bar{\nu}_e$.

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[7] Here we follow the more standard practice of using the momentum of the final-state baryon than that of the final vector meson as was done in Ref. 6. Thus the subsequent discussion on asymmetry parameters is defined in terms of the up-down asymmetry of the final baryon, etc. Under this change α, α', and β change sign, but γ, γ' do not change sign.