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From $\Xi_b \to \Lambda_b \pi$ to $\Xi_c \to \Lambda_c \pi$

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ABSTRACT

Using a successful framework for describing S-wave hadronic decays of light hyperons induced by a subprocess $s \to u(\bar{u}d)$, we presented recently a model-independent calculation of the amplitude and branching ratio for $\Xi_b^- \to \Lambda_b \pi^-$ in agreement with a LHCb measurement. The same quark process contributes to $\Xi_c^0 \to \Lambda_c \pi^-$, while a second term from the subprocess $cs \to cd$ has been related by Voloshin to differences among total decay rates of charmed baryons. We calculate this term and find it to have a magnitude approximately equal to the $s \to u(\bar{u}d)$ term. We argue for a negligible relative phase between these two contributions, potentially due to final state interactions. However, we do not know whether they interfere destructively or constructively. For constructive interference one predicts $\mathcal{B}(\Xi_c^0 \to \Lambda_c \pi^-) = (1.94 \pm 0.70) \times 10^{-3}$ and $\mathcal{B}(\Xi_c^+ \to \Lambda_c \pi^0) = (3.86 \pm 1.35) \times 10^{-3}$. For destructive interference, the respective branching fractions are expected to be less than about 10^{-4} and 2×10^{-4}.

1. Introduction

Most decays of charmed and beauty baryons observed up to now occur by c and b quark decays. In strange heavy flavor baryons an s quark may decay instead via the heavy flavor conserving subprocess $s \to u(\bar{u}d)$ or $su \to ud$, with the c or b quark acting as a spectator. In strange charmed baryons an additional Cabibbo-suppressed subprocess $cs \to cd$ can contribute. Early investigations of heavy flavor conserving two body hadronic decays of charmed and beauty baryons involving a low energy pion have been performed in Ref. [1–6]. In these studies a soft pion limit, partial conservation of the axial-vector current (PCAC) and current algebra have implied expressions for decay amplitudes in terms of matrix elements of four-fermion operators between initial and heavy baryon states. These matrix elements are difficult to estimate and depend strongly on models for heavy baryon wave functions.

Recently we proposed a model-independent approach for studying the decay $\Xi_b^- \to \Lambda_b \pi^-$ [7] which had just been observed by the LHCb collaboration at CERN [8]. In the heavy b quark limit this decay by $s \to u(\bar{u}d)$ proceeds purely via an S-wave. Assuming that properties of the light diquark in Ξ_b^- are not greatly affected by the heavy nature of the spectator b quark, the decay amplitude for $\Xi_b^- \to \Lambda_b \pi^-$ may be related to amplitudes for S-wave nonleptonic decays of Λ, Σ, and Ξ which have been measured with high precision [9]. We calculated a branching fraction for $\Xi_b^- \to \Lambda_b \pi^-$ consistent with the range allowed in the LHCb analysis. Our purpose now is to extend this calculation to charmed baryon decays $\Xi_c^0 \to \Lambda_c \pi^-$ and $\Xi_c^+ \to \Lambda_c \pi^0$.

Sec. 2 summarizes the result of Ref. [7] for the amplitude of $\Xi_b^- \to \Lambda_b \pi^-$, in which the underlying quark transition is $s \to u(\bar{u}d)$. This result is then applied to a contribution of the same quark subprocess to $\Xi_c^0 \to \Lambda_c \pi^-$. A second term in this amplitude due to the subprocess $cs \to cd$ is studied in Sec. 3. The total amplitude and the branching ratios for $\Xi_c^0 \to \Lambda_c \pi^-$ and $\Xi_c^+ \to \Lambda_c \pi^0$ are calculated in Sec. 4 while Section 5 concludes.

2. $s \to u(\bar{u}d)$ term in $\Xi_b^- \to \Lambda_b \pi^-$ and $\Xi_c^0 \to \Lambda_c \pi^-$

We will use notations which are common for describing hadronic hyperon decays [9]. The effective Lagrangian for $B_1 \to B_2 \pi$ given by

$$\mathcal{L}_{\rm eff} = G_F m_\pi^2 [\bar{\psi}_2 (A + B\gamma_5)\psi_1]\phi_\pi \tag{1}$$

involves two dimensionless parameters A and B describing S-wave and P-wave amplitudes, respectively. Here $G_F = 1.16638 \times 10^{-5}$ GeV^{-2} is the Fermi decay constant. The partial width is

$$\Gamma(B_1 \to B_2 \pi) = \frac{(G_F m_\pi^2)^2}{8\pi m_1^2} q [(m_1 + m_2)^2 - m_\pi^2]|A|^2 + [(m_1 - m_2)^2 - m_\pi^2]|B|^2 \,, \tag{2}$$

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Table 1
Predicted and observed S-wave amplitudes A for nonleptonic hyperon decays. Predicted values are for best-fit parameters $F = 1.652$, $x_0 = 0.861$.

Decay	Predicted A amplitude	Observed value [9]	Predicted value
$\Lambda \to p\pi^-$	$-(2F+1)x_0/\sqrt{6}$	-1.47 ± 0.01	-1.51
$\Lambda \to n\pi^0$	$(2F+1)x_0/(2\sqrt{3})$	1.07 ± 0.01	1.07
$\Sigma^+ \to n\pi^+$	0	0.06 ± 0.01	0
$\Sigma^+ \to p\pi^0$	$-(2F-1)x_0/\sqrt{2}$	-1.48 ± 0.05	-1.40
$\Sigma^- \to n\pi^-$	$-(2F-1)x_0$	-1.93 ± 0.01	-1.98
$\Xi^0 \to \Lambda\pi^0$	$(4F-1)x_0/(2\sqrt{3})$	1.55 ± 0.03	1.39
$\Xi^- \to \Lambda\pi^-$	$(4F-1)x_0/\sqrt{6}$	2.04 ± 0.01	1.97

where q is the magnitude of the final three-momentum of either particle in the B_1 rest frame.

Consider first $\Xi_b^- \to \Lambda_b\pi^-$ studied in Ref. [7]. In the heavy b quark limit the light quarks s and d in $\Xi_b^- = bsd$ are in an S-wave state antisymmetric in flavor with total spin $S = 0$. The light quarks u and d in the $\Lambda_b = bud$ are also in an S-wave state with $I = S = 0$. In the decay $\Xi_b^- \to \Lambda_b\pi^-$ which proceeds via $s \to u(\bar{u}d)$ the b quark acts as a spectator. The transition among light quarks is thus one with $J^P = 0^+ \to 0^+\pi$, and hence is purely a parity-violating S wave. Thus it may be related to parity-violating S-wave amplitudes in nonleptonic decays of the hyperons Λ, Σ, and Ξ.

S-wave hadronic decays of hyperons, $B_1 \to B_2\pi$, where the baryons B_1 and B_2 belong to the lowest SU(3) octet baryons, have been known for fifty years to be described well by using PCAC and current algebra and assuming octet dominance [10,11]. An equivalent and somewhat more compact parametrization of these amplitudes based on duality has been suggested a few years later [12]. All hyperon S-wave amplitudes may be expressed in terms of an overall normalization parameter x_0 and a parameter F describing the ratio of antisymmetric and symmetric three-octet coupling. (In the soft pion limit the commutator of the axial charge with the weak Hamiltonian represents a third octet in addition to the two baryons.) Thus one finds [7,12]

$$\begin{aligned} &A(\Lambda \to p\pi^-) = -(2F+1)x_0/\sqrt{6}\,, \\ &A(\Sigma^+ \to n\pi^+) = 0\,, \\ &A(\Sigma^- \to n\pi^-) = -(2F-1)x_0\,, \\ &A(\Xi^- \to \Lambda\pi^-) = (4F-1)x_0/\sqrt{6}\,, \end{aligned} \tag{3}$$

while amplitudes involving a neutral pion are related to these amplitudes by isospin. Using best fit values $F = 1.652$, $x_0 = 0.861$, one finds good agreement between predicted and measured amplitudes as shown in Table 1 (see [7]). The relative signs of S-wave amplitudes are convention-dependent and differ from those in Ref. [9]. An overall sign change is also permitted, associated with two possible signs of x_0.

In the decay $\Xi_b^- \to \Lambda_b\pi^-$, which also proceeds by $s \to u(\bar{u}d)$, the light diquarks sd and ud in the initial and final baryons form each a spinless antisymmetric 3^* of flavor SU(3). The weak transition occurs between this pair of diquarks while the b quark acts as a spectator. Neglecting the effect of the heavy b quark on relevant properties of the light diquarks, this amplitude is expected to be equal to an amplitude for a transition between light hyperons, $\Lambda \to \Lambda(\bar{u}u)$, in which the diquarks in initial and final hyperons are also in an antisymmetric 3^* while the s quark acts as a spectator. Thus one finds [7]

$$A(\Xi_b^- \to \Lambda_b\pi^-) = (5F-2)x_0/3\,. \tag{4}$$

Using the best fit values of x_0 and F one obtains $A(\Xi_b^- \to \pi^-\Lambda_b) = \pm 1.796$.

One may improve this calculation somewhat by including SU(3) breaking. We note that the measured S-wave amplitudes for $\Lambda \to p\pi^-$ and $\Sigma^- \to n\pi^-$ alone determine a slightly different value for x_0, $x_0 = 0.835$ having practically no effect on F. The relation

$$A(\Xi_b^- \to \Lambda_b\pi^-) = -\frac{1}{2\sqrt{6}}A(\Lambda \to p\pi^-) - \frac{3}{4}A(\Sigma^- \to n\pi^-)\,, \tag{5}$$

and experimental values of the amplitudes on the right-hand side imply

$$A(\Xi_b^- \to \Lambda_b\pi^-) = \pm 1.75 \pm 0.26\,. \tag{6}$$

In the three amplitudes occurring in (5) an s quark occurs in the decaying baryons taking part in the transition but not as a spectator. This leads to a common redefinition of x_0 which now includes SU(3) breaking. While the value (6) includes this effect of SU(3) breaking we have attributed to it an uncertainty of 15% caused by assuming octet dominance and by neglecting the effect of the heavy b quark on properties of the light diquarks.

The considerations and calculation leading to (6) apply also to the contribution of the transition $s \to u(\bar{u}d)$ to the S-wave amplitude for $\Xi_c^0 \to \Lambda_c\pi^-$. Here one replaces a spectator b quark in Ξ_b^- and Λ_b by a c quark in $\Xi_c^0 = csd$ and $\Lambda_c = cud$, assuming that the c quark mass is much heavier than the light u, d and s quarks. In this approximation we have

$$A_{s\to u\bar{u}d}(\Xi_c^0 \to \Lambda_c\pi^-) = A(\Xi_b^- \to \Lambda_b\pi^-)\,. \tag{7}$$

3. $cs \to cd$ contribution to $\Xi_c^0 \to \Lambda_c\pi^-$

The S-wave amplitude for $\Xi_c^0 \to \Lambda_c\pi^-$ obtains a second contribution from an "annihilation" subprocess $cs \to cd$ involving an interaction between the c and s quarks in the Ξ_c^0. We will now present in some detail a method proposed by Voloshin [3,13,14] for calculating this amplitude in the heavy c-quark limit in terms of differences among measured total widths of charmed baryons.

The effective weak Hamiltonian responsible for this Cabibbo-suppressed strangeness-changing transition is given by

$$\begin{aligned} H_W = -\sqrt{2}G_F\cos\theta_C\sin\theta_C\big[&(C_+ + C_-)(\bar{c}_L\gamma_\mu s_L)(\bar{d}_L\gamma_\mu c_L) \\ &+ (C_+ - C_-)(\bar{d}_L\gamma_\mu s_L)(\bar{c}_L\gamma_\mu c_L)\big]\,. \end{aligned} \tag{8}$$

In the following we will use values $C_+ = 0.80$ and $C_- = 1.55$ for Wilson coefficients calculated in a leading-log approximation at a scale $\mu = m_c = 1.4$ GeV corresponding to $\alpha_s(m_c)/\alpha(m_W) = 2.5$. Applying a soft pion limit and using PCAC, the amplitude due to $cs \to cd$ is given in our normalization (1) [which is related to that of Ref. [3] by a factor $\xi/(G_F m_\pi^2)$] by

$$\begin{aligned} &A_{cs\to cd}(\Xi_c^0 \to \Lambda_c\pi^-) \\ &= \frac{\sqrt{2}\xi}{f_\pi m_\pi^2}\cos\theta_C\sin\theta_C\langle\Lambda_c|(C_+ + C_-)(\bar{c}_L\gamma_\mu s_L)(\bar{u}_L\gamma_\mu c_L) \\ &\quad + (C_+ - C_-)(\bar{u}_L\gamma_\mu s_L)(\bar{c}_L\gamma_\mu c_L)|\Xi_c^0\rangle \\ &= \frac{\xi}{2\sqrt{2}f_\pi m_\pi^2}\cos\theta_C\sin\theta_C\,[0.75\,x - 2.35\,y]\,. \end{aligned} \tag{9}$$

Here $f_\pi = 0.130$ GeV, $\xi \equiv 2m_{\Xi_c^0}/\sqrt{(m_{\Xi_c^0} + m_{\Lambda_c})^2 - m_{\pi^-}^2} = 1.04$ [15].

In the above one defines two matrix element x and y (of dimension GeV^3) in which the contribution of the axial-current vanishes for a heavy c quark,