

Weak radiative decays of hyperons and of charm and beauty baryons *

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A review is presented of the weak radiative decays of baryons. It includes an analysis of the possible contributions of electromagnetic penguins to these decays, a survey of the difficulties still encountered in the sector of hyperon decays and a short account on some new developments on this topic. The theoretical treatments on charm and beauty baryon decays are summarized, with a good outlook for their detection.

1. INTRODUCTION

Although hyperon decays have been under scrutiny for some three decades the subject still carries the burden of a major puzzle and of discrepancies between existing data and a variety of theoretical models [1,2]. At the other end of the quark spectrum, there are no data yet on weak radiative decays of heavy baryons; however, estimates [3-6] for some of these modes allows us to anticipate optimistically their future detection.

In the (s, d, u) sector, the interesting weak radiative processes are two-body decays. These decays proceed with branching ratios of the order of $(1-3) \times 10^{-3}$, like $\Sigma^+ \rightarrow p\gamma$, $\Lambda \rightarrow n\gamma$, $\Xi^0 \rightarrow \Sigma^0\gamma$, or of the order 10^{-4} , like $\Xi^- \rightarrow \Sigma^-\gamma$ and the expected $\Omega^- \rightarrow \Xi^-\gamma$ [7]. The three-body decays $\Lambda \rightarrow p\pi^-\gamma$, $\Sigma^{+,-} \rightarrow n\pi^{+,-}\gamma$ proceed as expected for inner bremsstrahlung processes with branching ratios close to 10^{-3} and are not of our concern here. On the other hand, the two-body exclusive heavy baryon weak radiative processes like $\Lambda_b \rightarrow \Lambda^0\gamma$, $\Xi_b^- \rightarrow \Xi^-\gamma$ are not necessarily dominating the radiative channel and as we shall see one expects these modes to be substantially smaller than the inclusive ones, e.g. $BR[\Lambda_b \rightarrow X(s)\gamma] \gg BR[\Lambda_b \rightarrow \Lambda^0\gamma]$. Nevertheless, the study of the exclusive channels could provide important physical insights.

These weak radiative processes result from an interplay of electroweak and gluonic interactions. Presently, their theoretical treatment requires the inclusion of separate short-distance (SD) and long

distance (LD) contributions [8,9,10,5]. The estimate of the relative size of the two types of processes is an issue to be determined for every specific process. If, for instance, one is confident that in a certain process the long-distance emission is a rather small perturbation, like in $B \rightarrow X(x)\gamma$, $B \rightarrow K^*\gamma$, such processes may be assigned the strategic role of testing the Standard Model [11,12] as well as the testing of theories beyond it [13].

The next section surveys the possible role of the SD single-quark transition $Q \rightarrow q\gamma$ in the weak radiative decays of strange, charm and beauty baryons.

2. ELECTROWEAK PENGUINS IN BARYON RADIATIVE WEAK DECAYS

At the quark level there are three types of processes which contribute to the weak radiative decays of baryons, classified [14,15] as single-, two-, and three-quark transitions. The two-quark transition corresponds to W^- exchange, with the photon radiated by the participating quarks, and it is essentially a long-distance process. The three-quark transition, where the quark not participating in W -exchange radiates a photon, is strongly suppressed [15]. The single-quark transition involves a SD contribution due to the electromagnetic (EM) penguin diagrams [10,11,12] as well as possible LD contributions [16,17].

Before turning to the role of the EM penguins in the weak radiative baryon decays, one should mention the powerful analysis of Gilman and Wise (GW)[14]. In their paper, GW checked

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the hypothesis that *all* weak radiative hyperon decays in the 56-multiplet of SU(6) are driven by the single-quark transition $s \rightarrow d\gamma$. They determined the strength from the $\Sigma^+ \rightarrow p\gamma$ decay and proceeded to calculate from this the expected branching ratios for $\Lambda \rightarrow n\gamma$, $\Xi^0 \rightarrow \Sigma^0\gamma$, $\Xi^0 \rightarrow \Lambda\gamma$, $\Xi^- \rightarrow \Sigma^-\gamma$, $\Omega^- \rightarrow \Xi^-\gamma$ and $\Omega^- \rightarrow \Xi^{*-}\gamma$. Their predictions exceed the experimental rates by one or two orders of magnitude for the various decays. Thus, the hypothesis that *all these decays proceed via the single-quark transition is untenable*. However, it must be stressed that the analysis of GW does not preclude substantial contributions from $s \rightarrow d\gamma$, whether SD [18,19] or LD [17], in only some of the hyperon radiative decays.

In the standard electroweak model, the flavour-changing $Qq\gamma$ vertex with the Q, q quarks on the mass-shell has the form

$$\begin{aligned} \Gamma_\mu &= \frac{e}{4\pi^2} \frac{G_F}{\sqrt{2}} (q) \sum_\lambda V_{\lambda Q}^* V_{\lambda q} [F_{1,\lambda}(k^2)(k_\mu \not{k} \\ &- k^2 \gamma_\mu) \frac{1 - \gamma_5}{2} \\ &+ F_{2,\lambda}(k^2) i\sigma_{\mu\nu} k^\nu (m_Q \frac{1 + \gamma_5}{2} \\ &+ m_q \frac{1 - \gamma_5}{2})] (Q). \end{aligned} \quad (1)$$

$F_1(q^2)$ and $F_2(q^2)$ are the charge radius and magnetic form factors respectively, calculated [20] in electroweak theory in terms of masses of quarks and W ; V_{ab} are Cabibbo-Kabayashi-Maskawa (CKM) matrices. For $(sd\gamma)$ and $(bs\gamma)$ one has $\lambda = u, c, t$ and for $(cu\gamma)$ the contribution is from $\lambda = d, s, b$.

The F_1 term does not contribute to decays with real photons. It is, however, relevant in decays involving leptons like $B \rightarrow X(s)\ell^+\ell^-$ [21], $\Sigma^+ \rightarrow p\ell^+\ell^-$ [22], $\Omega^- \rightarrow \Xi^-\ell^+\ell^-$ [19]. In this paper we restrict our discussion to decays with real photons, to which only F_2 contributes.

The quantity of physical interest is the $Qq\gamma$ vertex with QCD corrections. The effective hamiltonian has the form

$$H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \lambda \sum C_i(\mu) O_i(\mu) \quad (2)$$

where λ represents symbolically products of CKM matrices, $O_i(\mu)$ is a complete set of dimension-

six operators and $C_i(\mu)$ are Wilson coefficients. Explicit expressions for the strange, charm and beauty sectors are given in Refs. [23], [24] and [12] respectively. $O_{1,2}$ are current-current operators, $O_3 - O_6$ are strong penguin operators and O_7, O_8 are magnetic operators, of EM and gluonic type respectively. In particular the EM penguin operator required by Eq. (1) has the form

$$\begin{aligned} O_7 &= \frac{e}{8\pi^2} (\bar{q})_\alpha \sigma^{\mu\nu} [m_Q(1 + \gamma_5) \\ &+ m_q(1 - \gamma_5)] (Q)^\alpha F_{\mu\nu}. \end{aligned} \quad (3)$$

The application of the QCD corrections using the renormalization group equations endows (3) with a coefficient C_7^{eff} , which is a linear combination of $C_i(\mu)$ and has been calculated for all three sectors, at least to leading order. We are thus in a position to determine quantitatively the contribution of the EM penguin to the baryonic radiative weak decays.

In the strangeness sector, the replacement by the QCD-corrections of a quadratic GIM cancellation by logarithmic dependence, increases F_2 by about three orders of magnitude [2,10]. The value of $C_7^{\text{eff}}(sd\gamma)$ has been reevaluated recently with better accuracy [17,25]. Using the new value we estimate the SD contribution to the typical pole decay $\Sigma^+ \rightarrow p\gamma$ and to the decays which have been singled out [18] as potential windows to $s \rightarrow d\gamma$, namely $\Omega^- \rightarrow \Xi^-\gamma$ and $\Xi^- \rightarrow \Sigma^-\gamma$. Using wave functions of Ref. [14] we find

$$\Gamma(\Sigma^+ \rightarrow p\gamma)_{s \rightarrow d\gamma}^{\text{SD}} / \Gamma(\Sigma^+ \rightarrow p\gamma)_{\text{exp}} = 2 \times 10^{-5} \quad (4)$$

Hence in hyperon radiative decays driven by LD poles the $s \rightarrow d\gamma$ transition does not play a noticeable role. On the other hand, one finds

$$\Gamma(\Omega^- \rightarrow \Xi^-\gamma)_{s \rightarrow d\gamma}^{\text{SD}} = 6.4 \times 10^{-12} \text{eV}. \quad (5)$$

Using the recently determined [26] upper limit $\Gamma(\Omega^- \rightarrow \Xi^-\gamma)_{\text{exp}} < 3.7 \times 10^{-9} \text{eV}$ one concludes [17] that in this decay the amplitude ratio SD/LD is larger than 1/25. Obviously, this is a remarkable result.

A similar calculation for $\Xi^- \rightarrow \Sigma^-\gamma$ gives

$$\Gamma(\Xi^- \rightarrow \Sigma^-\gamma)_{s \rightarrow d\gamma}^{\text{SD}} = 8.3 \times 10^{-13} \text{eV}, \quad (6)$$

which indicates a contribution of SD of about 4% in the amplitude of this decay.

The transition $c \rightarrow u\gamma$ has been treated in detail, including QCD corrections, only recently [24]. Contributions from all three quark loops are comparable in size, like in the strangeness sector. Likewise, the QCD corrections enhance also here enormously the transition, leading to a $c \rightarrow u\gamma$ width which is increased by five orders of magnitude. However, even with increased strength the $c \rightarrow u\gamma$ EM penguin is too small to play a role in weak hadronic radiative decays.

The $b \rightarrow s\gamma$ transition has been treated in great theoretical detail [12,27]. In this case, the contribution of the t -quark loop is strongly dominant so that other contributions are usually omitted. The recent measurements by CLEO of $B \rightarrow K^*\gamma$ [28] and $B \rightarrow X(\gamma)$ [29] confirm the original expectations [11] that these modes are dominated by the EM penguin transition $b \rightarrow s\gamma$. We expect therefore $b \rightarrow s\gamma$ to play a central role also in beauty baryon decays [5].

Hence, the role of the SD $Q \rightarrow q\gamma$ transition in the baryonic weak radiative decays is of different nature in each of the three sectors: it is totally negligible in the charm sector, it dominates the appropriate decays in the beauty sector, and plays a modest role in some of the hyperon decays like $\Omega^- \rightarrow \Xi^-\gamma$ and $\Xi^- \rightarrow \Sigma^-\gamma$.

3. THE HYPERON SECTOR

The amplitude for the transition $B(p) \rightarrow B'(p') + \gamma(k)$ is

$$M(B \rightarrow B'\gamma) = ieG_F \bar{u}(p') \sigma_{\mu\nu} (A + B\gamma_5) \epsilon^\mu k^\nu u(p) \quad (7)$$

where $A(B)$ are the parity-conserving (-violating) amplitudes. The angular distribution of the decay is characterized by an asymmetry parameter α_h , given by

$$\alpha_h = 2\text{Re}(A^*B)/(|A|^2 + |B|^2) . \quad (8)$$

Table 1 summarizes the experimental situation, based on Ref. [7] except for the entry on $\Omega^- \rightarrow \Xi^-\gamma$ which is based on a new experiment [26]. The recent analysis on the $\Sigma^+ \rightarrow p\gamma$ width based on 31900 events [30], not included in Table 1, gives $BR(\Sigma^+ \rightarrow p\gamma) = (1.20 \pm 0.06 \pm 0.05) \times 10^{-3}$.

A puzzling feature is the large negative asymmetry detected in $\Sigma^+ \rightarrow p\gamma$. According to Hara's theorem [31], in the limit of SU(3)-flavour symmetry the PV-amplitudes in $\Sigma^+ \rightarrow p\gamma$ and $\Xi^- \rightarrow \Sigma^-\gamma$ should vanish, causing a vanishing asymmetry. Many articles have been devoted to this question as exemplified by Ref. [32]. It has also been argued [33] that in a quark description the Hara theorem does not hold and the problem could lie in the "translation" of the quark basis to the hadronic world. So far, there is no convincing explanation for this large SU(3)-breaking.

A large number of models have been constructed to treat the processes of Table 1, most of them attempting a "unified" picture for the radiative hyperon decays. Among these models, there are pole models [34], quark models [15], skirmin models [35], Vector Meson Dominance models [36] and chiral models [37]. In many of these attempts, one accomplishes firstly a fit to the well measured $\Sigma^+ \rightarrow p\gamma$ mode, and predictions are made for other decays, though Refs. [35], [37] do not follow this pattern. Unfortunately, none of the existing models can reproduce simultaneously all the features in Table 1. In fact, comparing various models (see, e.g. Table 7.1 of Ref. [1] and Table II of Ref. [2]) one finds strong disagreements for the yet unmeasured quantities. In the following, we restrict ourselves to an analysis of the better understood physical features in these decays. The analysis of Section 2 has shown that the contribution of SD emission is negligible in the four decays proceeding at the 10^{-3} level, namely $\Sigma^+ \rightarrow p\gamma$, $\Lambda \rightarrow n\gamma$, $\Xi^0 \rightarrow \Sigma^0(\Lambda^0)\gamma$. It also can account for only a fraction of the decays proceeding at the 10^{-4} level or lower, $\Xi^- \rightarrow \Sigma^-\gamma$, $\Omega^- \rightarrow \Xi^-\gamma$, $\Omega^- \rightarrow \Xi^{*-}\gamma$, as already established for $\Xi^- \rightarrow \Sigma^-\gamma$ [9]. Thus, in all hyperon radiative decays the LD emission plays the predominant role. A further dynamical distinct arises from the valence quark structure of the hyperons and the explicit form of $H_{\text{eff}}^{\Delta S=1}$ (Eq. [2]). For the above group of four decays H_{eff} induces pole diagrams [e.g. $\Sigma \rightarrow (p, N^*) \rightarrow p\gamma$, etc.], which dominate over multiparticle intermediate states. A suitable combination of the $\frac{1}{2}^+$ baryons and $\frac{1}{2}^-$ resonance poles can lead to large asymmetries. However, the

Table 1
The experimental status of the hyperon radiative decays

Decay	Branching Ratio(10^{-3})	Asymmetry Parameter
$\Sigma^+ \rightarrow p\gamma$	1.25 ± 0.07	-0.76 ± 0.08
$\Lambda \rightarrow n\gamma$	1.75 ± 0.15	
$\Xi^0 \rightarrow \Sigma^0\gamma$	3.5 ± 0.4	0.20 ± 0.32
$\Xi^0 \rightarrow \Lambda^0\gamma$	1.06 ± 0.16	0.4 ± 0.4
$\Xi^- \rightarrow \Sigma^-\gamma$	0.127 ± 0.023	
$\Omega^- \rightarrow \Xi^-\gamma$	< 0.46	
$\Omega^- \rightarrow \Xi^{*-}\gamma$		

poor knowledge of some of the couplings involved leads to a widely divergent spectrum of predictions.

The second group of three decays involves particles $\Omega^-(sss)$, $\Xi^-(ssd)$, $\Sigma^-(sdd)$ with no u -valent quark, i.e. there are no W -exchange diagrams to generate poles. These decays will then proceed via two-hadron intermediate states. Gluonic penguins may also contribute; explicit calculations [38] indicate that such penguin contributions are considerably suppressed.

Thus, from a dynamical point of view, there are two distinct groups: the ‘‘pole decays’’ ($\Sigma^+ \rightarrow p\gamma$, $\Lambda \rightarrow n\gamma$, $\Xi^0 \rightarrow \Sigma^0\gamma$, $\Xi^0 \rightarrow \Lambda^0\gamma$) and the ‘‘non-pole decays’’ ($\Xi^- \rightarrow \Sigma^-\gamma$, $\Omega^- \rightarrow \Xi^-\gamma$, $\Omega^- \rightarrow \Xi^{*-}\gamma$), which are driven by different mechanisms. As an example of a ‘‘non-pole’’ calculation we mention $\Xi^- \rightarrow \Sigma^-\gamma$ [8], where the main LD contribution is due to the ($\Lambda\pi^-$) intermediate state. The imaginary part of Eq. (7) is then

$$ImM(\Xi^- \rightarrow \Sigma^-\gamma) = \frac{1}{2} \int \frac{d^4k}{(2\pi)^2} \delta(k^2 - m_\pi^2) \delta[(p - k)^2 - M_\Lambda^2] M(\Xi^- \rightarrow \Lambda\pi^-) \cdot T(\pi^- \Lambda \rightarrow \gamma\Sigma^-) \quad (9)$$

giving [9] $ImA^{LD} = 0.94\text{MeV}$, $ImB^{LD} = -8.3\text{MeV}$. For the real part, dominated by an infrared log divergence in the chiral limit, one finds $ReA^{LD} = 0$, $ReB^{LD} = -6.9\text{MeV}$. Including uncertainty one obtains [9]

$$\frac{\Gamma(\Xi^- \rightarrow \Sigma^-\gamma)}{\Gamma(\Xi^- \rightarrow \text{all})} = (1.8 \pm 0.4) \times 10^{-4};$$

$$\alpha_h(\Xi^- \rightarrow \Sigma^-\gamma) = -0.13 \pm 0.07. \quad (10)$$

The value for the width agrees well with experiment; the measurement of the asymmetry is required to confirm the physical picture.

4. A VECTOR MESON DOMINANCE APPROACH FOR LONG DISTANCE TRANSITIONS $Q \rightarrow q\gamma$

A new approach to the calculation of the LD contributions to the radiative decays $b \rightarrow s(d)\gamma$ has been suggested recently [16] and was applied to $s \rightarrow d\gamma$ and hyperon radiative decays in Ref. [17]. The basic idea is to calculate the LD emission via the t -channel, assuming the vector meson dominance (VMD) of the hadronic electromagnetic current [39]. A hybrid approach is employed in converting from the nonleptonic hamiltonian expressed in terms of quark operators to the process $Q \rightarrow qV \rightarrow q\gamma$. It should be mentioned that an older ‘‘ s -channel’’ attempt to calculate the LD contribution to $s \rightarrow d\gamma$ [40] uses a problematic mixture of particles and quarks on equal footing in intermediate loops.

Let us present the new approach [16,17] by considering the relevant O_1, O_2 operators in the $\Delta S = 1$ sector of Eq. (2)

$$H_{\text{eff}}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} \sum_{\eta=u,c,t} V_{\eta s} V_{\eta d}^* (C_{1,\eta} O_{1,\eta} + C_{2,\eta} O_{2,\eta}) + H.C. \quad (11)$$

$$O_{1,\eta} = \bar{d}\gamma_\mu(1 - \gamma_5)\eta_\beta\bar{\eta}\gamma^\mu(1 - \gamma_5)s, \quad (12a)$$

$$O_{2,\eta} = \bar{d}\gamma_\mu(1 - \gamma_5)\eta\bar{\eta}\gamma^\mu(1 - \gamma_5)s. \quad (12b)$$

Using factorization, one obtains the amplitude for $Q \rightarrow qV$ proportional to $a_2 g_V$, where $\langle V(k) | \bar{\eta}\gamma_\mu\eta | 0 \rangle = ig_V(k^2)\epsilon_\mu^+(k)$ and $a_2 = c_1 + \frac{C_2}{N}$, N being the number of colors. For the hyperon decays,

the $\eta = t$ contribution is negligible and using $V_{cs}V_{cd}^* \simeq -V_{us}V_{ud}^*$ and the Gordon decomposition to extract the transverse part, one has

$$A_{\text{LD}}^{s \rightarrow d\gamma} = -\frac{eG_F}{\sqrt{2}}V_{cs}V_{cd}^*a_2(\mu^2) \left[\frac{2}{3} \sum_i \frac{g_{\psi_i}^2(0)}{m_{\psi_i}^2} - \frac{1}{2} \frac{g_\rho^2(0)}{m_\rho^2} - \frac{1}{6} \frac{g_\omega^2(0)}{m_\omega^2} \right] \frac{1}{M_s^2 - M_d^2} \bar{d}\sigma^{\mu\nu}(M_s R - M_d L)sF_{\mu\nu}. \quad (13)$$

A phenomenological value $a_2(\mu^2) \geq 0.5$ is assumed [17]. M_s, M_d are constituent quark masses, R, L projection operators and the summation covers the six narrow $1^- \psi$ states.

The $\Omega^- \rightarrow \Xi^- \gamma$ decay is calculated [17] from (13) using the formalism of Ref. [14]. Using the experimental bound [26] of $\Gamma_{\text{exp}}(\Omega^- \rightarrow \Xi^- \gamma) < 3.7 \times 10^{-9} \text{eV}$ one obtains the relation

$$|C_{\text{VMD}}| = \left| \frac{2}{3} \sum_i \frac{g_{\psi_i}^2(0)}{m_{\psi_i}^2} - \frac{1}{2} \frac{g_\rho^2(0)}{m_\rho^2} - \frac{1}{6} \frac{g_\omega^2(0)}{m_\omega^2} \right| < 0.01 \text{GeV}^2. \quad (14)$$

The relation (14) represents a remarkable cancellation at the 30% level. It also determines $\sum_i g_{\psi_i}^2(0)/m_{\psi_i}^2 = 0.045 \pm 0.016 \text{GeV}^2$, implying a strong k^2 dependence in the $\psi_i - \gamma$ couplings which reduces their value by a factor of $\simeq 6$ from $k^2 = m_{\psi_i}^2$ to $k^2 = 0$. This conclusion agrees well with independent determinations of $g_{\psi_i}(0)$ from photoproduction and decays [16].

We expect $|C_{\text{VMD}}|$ to be quite close to the upper limit value (15), which in turn implies that $BR(\Omega^- \rightarrow \Xi^- \gamma)$ should be close to the experimental upper limit of Table 1. The two-body intermediate states contribute [8] to the BR of this decay only 0.8×10^{-5} . The application of this approach to $\Xi^- \rightarrow \Sigma^- \gamma$ gives for the LD contribution to the rate from $s \rightarrow dV$ an upper limit of 80%. For a pole decay like $\Sigma^+ \rightarrow p\gamma$ the same contribution is less than 1%. These values confirm the consistency of the dynamical picture discussed in this section.

5. CHARM BARYON DECAYS

Charm baryons containing one c quark are usually classified according to the SU(3) representation of the two light quarks, which can form a symmetric sextet (with spin 1) or an antisymmetric antitriplet (with spin 0). The spin $\frac{1}{2}$ antitriplet is composed of $\bar{B}_c^3(\Lambda_c^+, \Xi_c^+, \Xi_c^0)$. The sextet baryons have spin $\frac{1}{2}$ (B_c^6) or spin $\frac{3}{2}$ (B_c^{6*}). The particles forming it are $(\Sigma_c^{++}, \Sigma_c^+, \Sigma_c^0, \Xi_c^{*+}, \Xi_c^{*0}, \Omega_c^0)$. The \bar{B}_c^3 particles and Ω_c^0 decay weakly, while the rest of sextet particles decay strongly ($\Sigma_c^{+++,0} \rightarrow \Lambda_c^+ \pi^{+,0,-}$) or electromagnetically ($\Sigma_c^+ \rightarrow \Lambda_c^+ \gamma, \Xi_c^{+,0} \rightarrow \Xi^{+,0} \gamma$). In the following, we shall consider only two-body weak radiative decays of charm baryons.

The SD contribution from $c \rightarrow u\gamma$ to the radiative decays was shown to be negligible [24], hence the main mechanism for the decays is W -exchange. Since the radiative decays are “cleaner” than other weak multiparticle decay channels of B_c to strongly interacting particles, one may hope that their estimate will be quite reliable. We start our considerations by firstly classifying these decays according to their CKM strength:

CKM allowed decays ($\Delta C = \Delta S = -1$): $\Lambda_c^+ \rightarrow \Sigma^+ \gamma; \Xi_c^0 \rightarrow \Xi^0 \gamma$.

CKM forbidden decays ($\Delta C = -1; \Delta S = 0$): $\Lambda_c^+ \rightarrow p\gamma; \Xi_c^+ \rightarrow \Sigma^+ \gamma; \Xi_c^0 \rightarrow \Lambda(\Sigma^0)\gamma; \Xi_c^0 \rightarrow \Xi^0 \gamma$.

CKM doubly-forbidden decays ($\Delta C = -\Delta S = -1$): $\Xi_c^+ \rightarrow p\gamma; \Xi_c^- \rightarrow n\gamma; \Omega_c^0 \rightarrow \Lambda^0(\Sigma^0)\gamma$.

The photon energy in these decays is considerably larger than in the hyperon decays, ranging between 833 MeV in $\Lambda_c \rightarrow \Sigma^+ \gamma$ to 1124 MeV in $\Omega_c^0 \rightarrow \Lambda \gamma$.

Kamal has pioneered [3] this field by calculating $\Lambda_c^+ \rightarrow \Sigma^+ \gamma$ from two-quark W -exchange bremsstrahlung transitions of type $c+d \rightarrow s+u+\gamma$. Summing all relevant diagrams one obtains an effective Hamiltonian which is used to calculate the amplitudes A, B of Eq. (7). Using harmonic oscillator wave functions for the baryons involved, a branching ratio of nearly 10^{-4} is obtained. Upal and Verma [4] have improved the relativistic corrections of this calculation and have also introduced strong flavour dependence in the harmonic oscillator wave functions. The results of their two

Table 2.
Theoretical Estimates for Charm Baryon Decays

Decay Mode	Branching Ratio (10^{-4})				Asymmetry		
	Ref. [3]	Ref. [4] I	Ref. [4] II	Ref. [5]	Ref. [4] I	Ref. [4] II	Ref. [5]
$\Lambda_c \rightarrow \Sigma^+ \gamma$	0.67	0.45	2.9	0.49	-0.013	0.02	-0.86
$\Xi_c^0 \rightarrow \Sigma^0 \gamma$		0.19	1.3	0.31	-0.042	-0.01	-0.86

models, together with an updated value of Ref. [3] and results from a heavy-quark effective theory calculation [5] with c and s quarks as heavy are presented in Table 2 for the CKM allowed decays.

Branching ratios for the CKM-forbidden decays $\Lambda_c^+ \rightarrow p\gamma$, $\Xi_c^+ \rightarrow \Sigma^+\gamma$, $\Xi_c^0 \rightarrow \Lambda\gamma$, $\Omega_c^0 \rightarrow \Xi^0\gamma$ were also estimated in Ref. [4] and found to be generally of the order of 10^{-5} .

Finally, we comment on the weak radiative decays of heavy baryons with several c quarks. Among these, of particular interest is $\Xi_{cc}^+ \rightarrow \Xi_c^+\gamma$ which is CKM allowed and expected with a 10^{-4} branching ratio. There are also a couple decays which cannot proceed via W -exchange. These are $\Xi_{cc}^{++} \rightarrow \Sigma_c^{++}\gamma$ and $\Omega_{ccc}^{+++} \rightarrow \Xi_{cc}^{++}\gamma$, which could be driven by the $c \rightarrow u\gamma$ transition. Since the SD contribution is very small, these decays would constitute a direct window to the LD $c \rightarrow u\gamma$ process, or possibly to effects beyond the standard model.

6. BEAUTY BARYON DECAYS

As it was explained in Section 2, the SD contribution plays a prominent role in the b -sector. Therefore, we shall classify the beauty baryon two-body weak radiative decays as follows: (A) SD decays driven by the EM penguin $b \rightarrow s\gamma$, which includes $\Lambda_b^0 \rightarrow \Lambda^0\gamma$; $\Lambda_b^0 \rightarrow \Sigma^0\gamma$; $\Xi_b^0 \rightarrow \Xi^0\gamma$; $\Xi_b^- \rightarrow \Xi^-\gamma$; $\Omega_b^- \rightarrow \Omega^-\gamma$. (B) LD decays which are described on the quark level by two-quark W -exchange transitions accompanied by photon radiation. To this group belong $\Lambda_b^0 \rightarrow \Sigma_c^0\gamma$; $\Xi_b^0 \rightarrow \Xi_c^0\gamma$; $\Xi_b^- \rightarrow \Xi_c^-\gamma$. The decays in both groups are CKM doubly-forbidden, the matrix element being proportional to $V_{tb}V_{ts}^* \sim \lambda^2$ for group (A) and to $V_{ud}V_{bc}^* \sim \lambda^2$ for group (B). The photon energies are in the several GeV range, e.g. $E_\gamma = 2.71\text{GeV}$ for $\Lambda_b^0 \rightarrow \Lambda^0\gamma$.

Theoretical calculations for these decays were performed only recently [5,6]. For group (A) the transition amplitude for $B_i \rightarrow B_f\gamma$ is given by the short-distance QCD-corrected O_7 operator

$$M(B_i \rightarrow B_f\gamma) = \frac{iG_F}{\sqrt{2}} \frac{e}{4\pi^2} C_7^{\text{eff}} V_{tb}V_{ts}^* \epsilon^\mu k^\nu \langle \bar{B}_f | \bar{s}\sigma_{\mu\nu} [m_b(1 + \gamma_5) + m_s(1 - \gamma_5)] b | B_i \rangle \quad (15)$$

where $C_7^{\text{eff}} = 0.31$ [24,27]. The LD contribution to the $b \rightarrow s\gamma$ transition is estimated to be at the level of a few percent only [16,17], which allows us to neglect it. The authors of Ref. [5] use two methods to treat the $\Lambda_b \rightarrow \Lambda\gamma$ decay, - the heavy quark symmetry scheme with both b and s treated as heavy, and the MIT bag model. In the first method, they obtain for the A,B amplitudes of Eq. (7)

$$A, B = \frac{C_7^{\text{eff}}}{4\sqrt{2}\pi^2} V_{tb}V_{ts}^* \left(1 \pm \frac{m_s}{m_b} - \frac{\bar{\Lambda}h}{2m_s} \right) \xi(v \cdot v') \quad (16)$$

where $\xi(v \cdot v')$ is the Isgur-Wise function and h is a function of $v \cdot v'$. Allowing for reasonable variation of the various parameters involved, Cheng et al. [5] conclude that

$$BR(\Lambda_b^0 \rightarrow \Lambda^0\gamma) = (0.5 - 1.5) \times 10^{-5} \quad (17)$$

From their amplitude, one obtains $\alpha_h(\Lambda_b^0 \rightarrow \Lambda^0\gamma) = 0.9$.

In the heavy s quark limit, Λ^0 behaves as an antitriplet heavy baryon while Σ^0 as a sextet heavy baryon. Λ_b^0 belongs to an antitriplet. Accordingly, $b \rightarrow s\gamma$ will not induce in the limiting case $\Lambda_b^0 \rightarrow \Sigma^0\gamma$ which is a sextet-antitriplet transition and one is led to

$$\Gamma(\Lambda_b^0 \rightarrow \Sigma^0\gamma) \ll \Gamma(\Lambda_b^0 \rightarrow \Lambda^0\gamma) \quad (18)$$

The other decays of group (A) are more difficult to treat (several heavy quarks baryon). In any case, branching ratios somewhat smaller than in Eq. (17) are expected, also due to wave function overlap suppression especially in $\Omega_b^- \rightarrow \Omega^- \gamma$.

For the transitions of group (B) an effective Lagrangian is constructed [5] from the diagrams of the W -exchange bremsstrahlung processes $b + u \rightarrow c + d + \gamma$, $b + \bar{d} \rightarrow c + \bar{u} + \gamma$. Branching ratios smaller by at least one order of magnitude than in group (A) are obtained [5], even if maximal overlap for the static bag wave functions is assumed:

$$\begin{aligned} BR(\Xi_b^0 \rightarrow \Xi_c^0 \gamma) &= 6.4 \times 10^{-8}; \alpha_h = -0.47 \\ BR(\Xi_b^0 \rightarrow \Xi_c^{\prime 0} \gamma) &= 5.7 \times 10^{-7}; \alpha_h = -0.98 \\ BR(\Lambda_b^0 \rightarrow \Sigma_c^0 \gamma) &= 1.2 \times 10^{-6}; \alpha_h = -0.98 \end{aligned}$$

The basic decay mechanism $b \rightarrow s \gamma$ actually leads to a multitude of exclusive states in the radiative Λ_b decay, like $\Lambda_b \rightarrow \Lambda(1405)\gamma$, $\Lambda(1520)\gamma$, $\Lambda(n\pi)\gamma$, $\Lambda\eta\gamma$, $\Lambda\eta'\gamma$, etc. Hence it is of interest to estimate the expected $\Lambda_b^0 \rightarrow X(s)\gamma$ branching ratio and the percentage of it of the lowest exclusive mode, $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$. We use the measured [29] $B \rightarrow X(s)\gamma$ to calculate $\Gamma(b \rightarrow s\gamma) = (1 \pm 0.35) \times 10^{-7} \text{eV}$. Assuming $\Gamma(\Lambda_b^0 \rightarrow X(s)\gamma)/\Gamma(\Lambda_b \rightarrow \text{all}) \simeq \Gamma(b \rightarrow s\gamma)/\Gamma(\Lambda_b \rightarrow \text{all})$ and the measured Λ_b^0 life-time[7] we estimate

$$\frac{\Gamma(\Lambda_b^0 \rightarrow X(s)\gamma)}{\Gamma(\Lambda_b \rightarrow \text{all})} = (1.6 \pm 0.5) \times 10^{-4}. \quad (19)$$

Hence, the calculations presented above lead to

$$\frac{\Gamma(\Lambda_b^0 \rightarrow \Lambda^0 \gamma)}{\Gamma(\Lambda_b \rightarrow X(s)\gamma)} \simeq (6.0 \pm 3.5)\%. \quad (20)$$

The figure we obtained is not very different from the mesonic sector, where one has [28,29] $\Gamma(B \rightarrow K^* \gamma)/\Gamma(B \rightarrow X(s)\gamma) = 0.2 \pm 0.1$

An analysis [41] of the angular distribution of the photon in $\Lambda_b^0 \rightarrow X(s)\gamma$ with polarized Λ_b^0 , using the heavy quark effective scheme, shows that deviations from free quark decay are generally small and are significant mostly for photons emitted in the forward direction with respect to Λ_b^0 spin. However, as a consequence of the functional form of the EM penguin the photons are emitted preferentially backwards.

7. CONCLUDING REMARKS

We highlight here several points, some of which are of direct relevance to forthcoming and contemplated experimental programmes:

As a result of the theoretical activity of last few years, a clear picture emerges on the the importance of short-distance radiation in the weak radiative decays of baryons. Thus, the electromagnetic penguin $Q - q\gamma$ (with gluonic corrections) plays a major role in the beauty sector, dominating processes like $\Lambda_b \rightarrow X(s)\gamma$, $\Lambda_b \rightarrow \Lambda\gamma$. The charm penguin $c \rightarrow u\gamma$ is too weak to play any noticeable role in charm baryon radiative decays, while the strange penguin $s \rightarrow d\gamma$ occupies an intermediate position, contributing to a possibly detectable extent in a few hyperon decays ($\Omega^- \rightarrow \Xi^- \gamma$, $\Xi^- \rightarrow \Sigma^- \gamma$, $\Omega^- \rightarrow \Xi^{*-} \gamma$).

The measurements of the rate and asymmetry parameter of $\Omega^- \rightarrow \Xi^- \gamma$ should be given high priority, since there is good probability that both SD and LD radiation contributes measurably to it. This decay could constitute the main desired window to the EM penguin in the strangeness sector $s \rightarrow d\gamma$, in addition to providing interesting information on couplings of vector mesons to photons from the LD contribution.

It is difficult at present to favour any of the competing models describing pole hyperon decays like $\Sigma^+ \rightarrow p\gamma$, $\Xi^0 \rightarrow \Sigma^0 \gamma$, etc. Since the various models diverge mostly in the prediction of the asymmetry parameter, good measurements of this parameter in $\Lambda \rightarrow n\gamma$, $\Xi^0 \rightarrow \Lambda\gamma$ and $\Xi^0 \rightarrow \Sigma^0 \gamma$ should finally allow one to resolve the unsettled situation.

The measurement of the asymmetry parameter in the decay $\Xi^- \rightarrow \Sigma^- \gamma$ will distinguish between the dynamical picture [8,9] for non-pole decays which leads to Eq. (10), and alternative mechanisms [34-37].

Theoretical estimates indicate that charm baryon CKM allowed radiative decays will occur with a branching ratio of $\sim 10^{-4}$, making the search for these decays a realistic proposition. One expects $BR(\Lambda_c^+ \rightarrow \Sigma^+ \gamma) = 1_{-0.5}^{+1} \times 10^{-4}$, $BR(\Xi_c^0 \rightarrow \Xi^0 \gamma) = (0.8 \pm 0.5) \times 10^{-4}$. The CKM-forbidden decays, like $\Lambda_c^+ \rightarrow p\gamma$, $\Xi_c^0 \rightarrow \Lambda(\Sigma^0)\gamma$, $\Xi_c^+ \rightarrow \Sigma^+ \gamma$, $\Omega_c^0 \rightarrow \Xi^0 \gamma$ are expected to occur

with branching ratios of 10^{-5} or less.

Beauty baryons have detectable weak radiative decays induced by short distance electromagnetic penguins. The inclusive decay $\Lambda_b \rightarrow X(s)\gamma$ is expected to have a branching ratio of $(1.6 \pm 0.5) \times 10^{-4}$. The most frequent exclusive mode is probably $\Lambda_b \rightarrow \Lambda\gamma$ expected to occur with a branching ratio of $(1 \pm 0.5) \times 10^{-5}$. On the other hand, $\Lambda_b^0 \rightarrow \Sigma^0\gamma$ is expected from heavy quarks symmetry considerations to be much smaller. Radiative decays to charm baryons $\Lambda_b^0 \rightarrow \Sigma_c^0\gamma$, $\Xi_b^0 \rightarrow \Xi_c^0\gamma$, $\Xi_b^0 \rightarrow \Xi_c^{\prime 0}\gamma$ are expected in the $10^{-6} - 10^{-7}$ range.

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