TTP97-38*
hep-ph/9710287
October 1997

Probing the helicity structure of $b \to s\gamma$ in $\Lambda_b \to \Lambda\gamma$

Presented at XXIst School of Theoretical Physics, Ustron 97

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Abstract

We investigate the rare decay $\Lambda_b \to \Lambda\gamma$ which receives both short and long distance contributions. We estimate the long distance contributions and find them very small. The form factors are obtained from $\Lambda_c \to \Lambda\ell\bar{\nu}_\ell$ using heavy quark symmetry and a pole model. The short distance piece opens a window to new physics and we discuss the sensitivity of $\Lambda_b \to \Lambda\gamma$ to such effects.

1 Introduction

Flavour Changing Neutral Current (FCNC) processes have attracted renewed attention since the recent CLEO measurement of the FCNC decays of the type $b \to s\gamma$. Since in the Standard Model (SM) these processes are forbidden at the tree level and hence are strongly suppressed by the GIM mechanism, they offer a unique possibility to test the CKM sector of the SM.

Based on the decays of B mesons it will not be possible to analyse the helicity structure of the effective hamiltonian mediating the decay $b \to$

*The complete paper, including figures, is also available via anonymous ftp at ftp://ttpux2.physik.uni-karlsruhe.de/, or via www at
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$s\gamma$, since the information on the handedness of the quarks is lost in the hadronization process. The only chance to access the helicity of the quarks is to consider the decay of baryons.

Heavy–to–light transitions between ground state baryons are in large parts of the phase space restricted by heavy quark symmetries. For the baryonic transition $\Lambda_Q \to$ light spin-1/2 baryon the number of independent form factors is restricted to only two. However, it is expected that heavy quark symmetries work best for such a kinematic configuration where the outgoing light hadron is almost at rest, corresponding to the point of maximum momentum transfer. For the decay under consideration, $b \to s\gamma$, we are at the opposite side of phase space where $q^2 = 0$. We shall still use the relations implied by heavy quark symmetry although there is no *a priori* reason to expect that they hold at $q^2 = 0$. This is motivated from models based on the diquark picture which phenomenologically work quite well.

Another theoretical difficulty with the process suggested is possible long distance contributions which will dilute the effects of a non–SM–contribution to the short distance effective hamiltonian for $b \to s\gamma$. Such contributions can only be estimated in terms of models but they turn out to be small.

2 The decay amplitude for $\Lambda_b \to \Lambda\gamma$

The effective hamiltonian for this specific decay consists in the SM of only one operator, in which (up to tiny effects from the strange quark mass) the b–quark is right–handed and the s–quark is left–handed. Generalizing this we introduce couplings constants g_V and g_A such that the effective hamiltonian takes the form:

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} C_7 \mathcal{O}_7, \quad \mathcal{O}_7 = \frac{e}{32\pi^2} m_b \bar{s} \sigma_{\mu\nu}(g_V - g_A\gamma_5) b F^{\mu\nu} \qquad (1)$$

In the Standard Model $g_V = 1 + m_s/m_b, g_A = -1 + m_s/m_b$ and $C_7 = 0.325$ from a leading log QCD calculation. We shall use $C_7 g_V$ and $C_7 g_A$ as parameters describing strength and helicity structure of the short distance process.

It remains to calculate matrix elements of the operators. In the present case we shall make use of the fact that the b quark is heavy, while the s quark is taken to be a light quark. In general, heavy quark symmetries restrict the number of possible form factors quite significantly; in the present case there are only two, parametrized by [1]

$$\langle \Lambda(p,s) | \bar{s}\Gamma b | \Lambda_b(v,s') \rangle = \bar{u}_\Lambda(p,s)\{F_1(p.v) + \not{v} F_2(p.v)\}\Gamma u_{\Lambda_b}(v,s') \qquad (2)$$

Γ is an arbitrary Dirac matrix, such that any transition between a Λ_Q ($Q = b, c$) and a light spin 1/2 baryon is given by the same form factors. As mentioned in the introduction, (2) is expected to work best at q^2_{max}, but we shall use this relation also at $q^2 = 0$, which is in the worst case a model assumption.

The quantity of interest is the decay rate of unpolarized Λ_b baryons into Λ baryons with a definite spin directions s. This rate can be written in terms of the polarization variables as defined in [3]

$$\Gamma = \Gamma_0 \cdot [1 + \alpha' \hat{\mathbf{p}}.\mathbf{S}_\Lambda] \tag{3}$$

where $\hat{\mathbf{p}}$ is the momentum vector of the Λ and $\mathbf{S}_\Lambda$ is its spin vector. Here Γ_0 depends on the sum $g_V^2 + g_A^2$ only and the other dependence on g_V and g_A is contained in

$$\alpha' \;=\; 0.378 \cdot \frac{2 g_V g_A}{g_V^2 + g_A^2}. \tag{4}$$

The polarization variable depends only on the ratio of the form factors for which we have assumed a constant value and which has been extracted by CLEO to be [2] $R = F_2/F_1 = -0.25 \pm 0.14 \pm 0.08$. Furthermore we have used he ratio of the baryon masses $x = 0.20$.

In addition to the short distance part there are also long distance contributions to $\Lambda_b \to \Lambda\gamma$: One type of long distance contributions involves a virtual J/Ψ that subsequently decays into the final state photon, this is a vector meson dominance like contribution. The other type of short distance contribution arises from a W–boson being exchanged between two of the internal quark lines, the photon is radiated off any of the internal quark lines.

We have estimated both these contributions employing a vector dominance type model in combination with factorization and a simple diquark picture for the internal W–exchange. Both contributions are small; the former can be expressed as a correction to the short distance couplings g_V and g_A (magnitude indicated by the width of the lines in Fig.1) and the latter one is negligible.

3 The decay rate and polarization asymmetry for $\Lambda_b \to \Lambda\gamma$

We extract the relevant form factors from the decay $\Lambda_c \to \Lambda \ell \bar{\nu}_\ell$, which is according to (2) given by the same two form factors as $\Lambda_b \to \Lambda\gamma$. To do so we must make a model for the q^2–dependence of the form factors. Starting from a simple pole model,

$$F_{1/2}(q^2) = F_{1/2}^{\max} \cdot \left(\frac{M_{1/2}^2 - m_Q^2}{M_{1/2}^2 - q^2} \right)^n , \quad n = 1, 2 , \tag{5}$$

where $M_{1/2}$ is the mass of the nearest resonance with the correct quantum numbers for F_1 and F_2, we use the relation between q^2 and $v.p$ as well as heavy quark symmetry to obtain

$$F_{1/2}(p.v) = N_{1/2} \cdot \left(\frac{\Lambda}{\Lambda + p.v} \right)^n , \quad n = 1, 2 , \tag{6}$$

where $\Lambda = 200 MeV$ is found from the masses of the respective resonances for both form factors. In (5) and (6) $n = 1$ and $n = 2$ denote monopole and dipole phase space depencence, respectively. We shall give our final results for both these models. For simplicity we have assumed the same $v.q$–dependence for both of the form factors which again allows us to use the phase space averaged measurement of $\langle F_2/F_1 \rangle = -0.25 \pm 0.14 \pm 0.08$[2] for the ratio of $F_1^{\max}$ and $F_2^{\max}$.

Using the data for rate for $\Lambda_c \to \Lambda \ell \bar{\nu}_\ell$ [3] we obtain an expression for the total decay rate of $\Lambda_b \to \Lambda\gamma$ in which only the depencence on the fifth power of the mass of the b quark introduces a sizable uncertainty. To eliminate this uncertainty we compare the decay $\Lambda_b \to \Lambda\gamma$ to the semileptonic decay of the B meson which exhibits the same m_b^5 dependence. Using the lifetimes and the inclusive semileptonic branching fraction $BR(B \to X_c l \nu) = (10.3 \pm 1.0)\%$ from [3] we obtain

$$BR(\Lambda_b \to \Lambda\gamma) = (1 - 4.5) \cdot 10^{-5}, \tag{7}$$

where the lower and upper value correspond to the dipole and monopole q^2 evolution of the form factors, respectively.

For values of g_A and g_V different from the standard model ones one has to multiply the above equation by the factor $(g_A^2 + g_V^2)/2$, neglecting the strange quark mass and the long distance contributions.

In the following we shall use the measurement of the inclusive rate $B \to X_s\gamma$ to fix $(g_V C_7)^2 + (g_A C_7)^2$; in the $C_7 g_V$–$C_7 g_A$–plane a measurement of any total rate (meaning any of the processes $B \to X_s\gamma$, $B \to K^*\gamma$ or $\Lambda_b \to \Lambda\gamma$) will correspond to a circle, since all these decay rates are proportional to $(g_V C_7)^2 + (g_A C_7)^2$.

If in future experiments a measurement of α' in $\Lambda_b \to \Lambda\gamma$ is performed one may use the relation between α' and $(C_7 g_A)/(C_7 g_V)$. Including our estimate of the long distance contributions, one obtains

$$C_7 g_A = (C_7 g_V + C_7 \rho)\left(\frac{0.353}{\alpha'} \pm \sqrt{\left(\frac{0.353}{\alpha'}\right)^2 - 1}\right) + C_7 \rho \qquad (8)$$

which corresponds to straight lines in the $C_7 g_A$–$C_7 g_V$ plane.

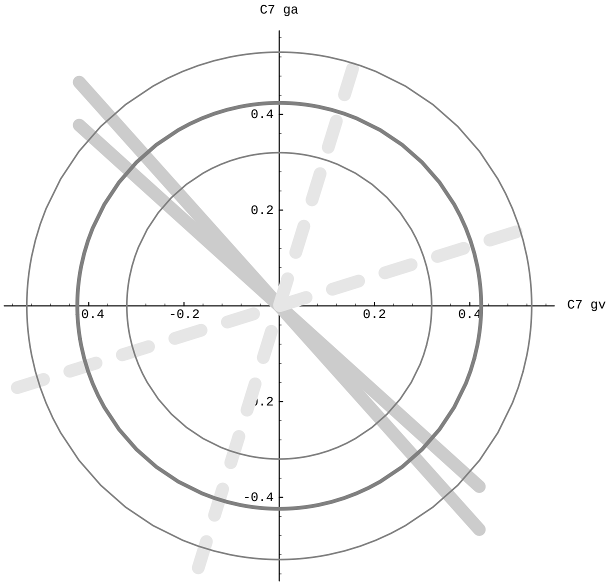

Figure 1: The $C_7 g_A$–$C_7 g_V$ plane

In fig.1 we plot the $C_7 g_A$–$C_7 g_V$ plane. The central circle corresponds to the central value of the measurement of $B \to X_s \gamma$ and the thin circles indicate the experimental uncertainty. Assuming the standard model values for $C_7 g_A$ and $C_7 g_V$ we have also plotted the corresponding lines. The width of these lines is given by our estimate for the long distance contributions; we have taken this estimate as an additional uncertainty meaning that the width of these lines is $2\rho C_7$.

A measurement of α' yields in general two lines which have in total four intersections with the circle. The two intersections of each line correspond to a sign interchange $g_A \to -g_A$ and at the same time $g_V \to -g_V$ which is an unobservable phase. The remaining ambiguity corresponds to the interchange $g_A \to g_V$ and $g_V \to g_A$, since the polarization variable and the total rate are symmetric functions of g_A and g_V. Graphically this means that the two lines for a measured value of α' are mirror images of each other with respect to the lines $g_A = |g_V|$. In order to resolve this ambiguity additional measurements would be necessary.

In the SM $|g_A| \approx |g_V|$ ($\alpha' = -0.351$) up to corrections from the non-vanishing s quark mass, therefore the two solid lines almost coincide for the SM value of α'. For illustrations we also have plotted two dashed lines for a hypothetical measurement of $\alpha' = 0.2$.

With a branching ratio for $\Lambda_b \to \Lambda\gamma$ of the order 10^{-5} one needs 10^8 b quarks to have about one hundred events, without applying cuts for efficiencies. Clearly this will be feasible at dedicated b physics experiments at colliders such as the one at Tevatron or LHC, and possibly also at fixed target experiments like HERA-B.

References

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