Orissa Journal of Physics
ISSN 0974-8202

Vol. 22, No.1
February 2015
pp. 1-8

Signal of New Physics from the Study of Rare $\Lambda_b \to \Lambda e^+e^-$ decay in Z'-Model

C DHARAI, D BANERJEE and S. SAHOO[1]

Department of Physics, National Institute of Technology,
Durgapur - 713209, West Bengal, India.
[1]E-mail: sukadevsahoo@yahoo.com

Received : 10.11.2014 ; Accepted : 13.1.2015

Abstract : In this paper, the effect of Z'-mediated flavor-changing neutral current on $\Lambda_b \to \Lambda e^+e^-$ rare decay has been studied. We find the branching ratio is reasonably enhanced from its standard model value and gives the possibility of new physics beyond the standard model. The contribution of Z'-boson depends upon the precise value of $M_{Z'}$.

Keywords: Z-boson; Z'-boson; Semileptonic baryonic decays; Heavy quark effective theory

PACS Nos.: 14.70.Hp; 14.70.Pw; 13.30.Ce; 12.39.Hg

1. Introduction

Rare B decays induced by flavor-changing neutral current (FCNC) $b \to s(d)\ell^+\ell^-$ transitions are very important to probe the flavor sector of the standard model (SM). The rare decays $\Lambda_b \to \Lambda \ell^+\ell^-$ $(\ell = e, \mu, \tau)$ [1–3] which are induced by FCNC can be described by the processes $b \to s\,\ell^+\ell^-$ at the quark level. In the SM, these FCNC transitions are forbidden at tree level, while can occur at loop level. New physics (NP) comes into play in rare B decays in two different ways: (a) through a new contribution to the Wilson coefficients or (b) through a new structure in the effective Hamiltonian, which are both absent in the SM. Rare decays can give valuable information about the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, V_{td}, V_{ts}, V_{tb}, etc and leptonic decay constants.

Z'-bosons theoretically exist in grand unified theories (GUTs), superstring theories and theories with large extra dimensions [4] but experimentally the Z'-boson is not discovered so far [5]. If the Z'-bosons couple to quarks and leptons not too weakly and if their mass is not too large, they will be produced at the Tevatron and the LHC and easily detected through their leptonic decay modes [6]. Therefore the search for these particles is a very challenging topic in experimental physics. In the Z' model [7], the FCNC $b-s-Z'$ coupling is related to the flavor-diagonal couplings qqZ' in a predictive way, which is then used to obtain upper limits on the leptonic $\ell\ell Z'$ couplings. Hence, it is possible to predict the branching ratio for $\Lambda_b \to \Lambda\ell^+\ell^-$ rare decay. With FCNCs, both Z and Z'-boson contributes at tree level, and its contribution will interfere with the SM contributions. Sahoo et al. [8] have already studied $\Lambda_b \to \Lambda\ell^+\ell^-$ $(\ell = \mu, \tau)$ decays in the Z'-model. In this paper, we study $\Lambda_b \to \Lambda e^+e^-$ rare decay considering the effect of both Z and Z'-mediated FCNCs that change the effective Hamiltonian and modifies the branching ratio.

This paper is organized as follows: in Section 2, we discuss the $\Lambda_b \to \Lambda\ell^+\ell^-$ rare decay in the SM. In Section 3, we evaluate the effective Hamiltonian for $\Lambda_b \to \Lambda e^+e^-$ rare decay considering the contributions from both the Z and Z'-bosons. In Section 4, we calculate the branching ratio for $\Lambda_b \to \Lambda e^+e^-$ decay. Then we discuss our results.

2. $\Lambda_b \to \Lambda\ell^+\ell^-$ Decay in the Standard Model

Let us consider the $\Lambda_b \to \Lambda\ell^+\ell^-$ $(\ell = e, \mu, \tau)$ rare decay process. In the SM, this process is loop-suppressed. However, it is potentially sensitive to new physics beyond the SM. At the quark level, the $\Lambda_b \to \Lambda\ell^+\ell^-$ decay is described by the $b \to s\ell^+\ell^-$ transition. The matrix element of the $b \to s\ell^+\ell^-$ process contains terms describing the virtual effects induced by $t\bar{t}, c\bar{c}$ and $u\bar{u}$ loops which are proportional to $V_{tb}V_{ts}^*, V_{cb}V_{cs}^*$ and $V_{ub}V_{us}^*$ respectively. From unitarity of the CKM matrix and neglecting $V_{ub}V_{us}^*$ in comparison to $V_{tb}V_{ts}^*$ and $V_{cb}V_{cs}^*$, it is clear that the matrix element of the $b \to s\ell^+\ell^-$ contains only one independent CKM factor $V_{tb}V_{ts}^*$. The effective Hamiltonian describing $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay process is given [2,9]:

$$H_{eff} = \frac{G_F\,\alpha}{\sqrt{2}\,\pi}\lambda_t \,[\; C_9^{eff}\left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right) + C_{10}\left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu \gamma_5\,\ell\right) - 2C_7^{eff} m_b \left(\bar{s}\, i\sigma_{\mu\nu}\frac{p^\mu}{p^2} P_R\, b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right)\,], \tag{1}$$

where G_F is the Fermi coupling constant, α is the electromagnetic coupling constant, $\lambda_t = V_{tb}V_{ts}^*$, $P_{R,L} = \frac{1}{2}\left(1 \pm \gamma_5\right)$, p is the momentum transferred to the lepton pair and $p = p_+ + p_-$ the sum of the momenta of the ℓ^+ and ℓ^-, and C_7^{eff}, C_9 and C_{10} are Wilson coefficients evaluated at the b quark mass scale in the modified minimal subtraction $\left(\overline{MS}\right)$ scheme ($m_b = 4.6$ GeV).

The amplitude of $\Lambda_b\left(p_{\Lambda_b}\right) \to \Lambda\left(p_\Lambda\right)\ell^+\left(p_+\right)\ell^-\left(p_-\right)$ decay can be obtained by sandwiching H_{eff} for the $b \to s\,\ell^+\ell^-$ transition between initial and final baryon states i.e. $\left\langle \Lambda \middle| H_{eff} \middle| \Lambda_b \right\rangle$ [2,8]. Then the double partial decay rates for $\Lambda_b \to \Lambda e^+ e^-$ can be obtained from the transition amplitude as:

$$\frac{d^2\Gamma}{d\hat{s}\,dz} = \frac{G_F^2\,\alpha^2\,\lambda_t^2}{2^{12}\,\pi^5}\, m_{\Lambda_b}\sqrt{1 - \frac{4m_l^2}{p^2}}\,\sqrt{\lambda\left(1, r, \hat{s}\right)}\,K\left(s, z\right), \tag{2}$$

where $\hat{s} = s/m_{\Lambda_b}^2$, $z = \cos\theta$, the angle between p_{Λ_b} and p_+ in the center of mass frame of $\ell^+\,\ell^-$ pair, and $\lambda\left(a, b, c\right) = a^2 + b^2 + c^2 - 2\left(ab + bc + ca\right)$ is the usual triangle function. The function $K\left(s, z\right)$ is given in [8]. The limits for s are based on the kinematic phase space:

$$4m_l^2 \le s \le \left(m_{\Lambda_b} - m_\Lambda\right)^2 . \tag{3}$$

The branching ratios can be calculated by multiplying decay width Γ with the life time of Λ_b i.e.

$$B\left(\Lambda_b \to \Lambda\ell^+\ell^-\right) = \Gamma\left(\Lambda_b \to \Lambda\ell^+\ell^-\right)\tau_{\Lambda_b} , \qquad (4)$$

where τ_{Λ_b} is the life time of Λ_b and $\tau_{\Lambda_b} = \left(1.383^{+0.049}_{-0.048}\right) \times 10^{-12}$ s [10]. The value of the branching ratios for $\Lambda_b \to \Lambda e^+ e^-$ decay in the SM [3] is given as:

$$\mathrm{B}\left(\Lambda_b \to \Lambda e^+ e^-\right) = \left(4.6 \pm 1.6\right) \times 10^{-6}. \qquad (5)$$

3. $\Lambda_b \to \Lambda e^+ e^-$ Decay in Z-mediated and Z'-mediated FCNC Model

Let us consider the $\Lambda_b \to \Lambda\ell^+\ell^-$ **(**$\ell = e$**)** decay process in the presence of Z-mediated FCNC [11] at tree level. The Zbs FCNC coupling, which affects B-decays, is parameterized by one independent parameter U_{sb} and this parameter is constrained by branching ratio of the process $B \to X_S\ell^+\ell^-$ and is found to be $\left|U_{sb}\right| \cong 1\times 10^{-3}$ [12]. Considering the contribution of the Z-boson to $\Lambda_b \to \Lambda e^+ e^-$ decay, one can write the effective Hamiltonian [2] as

$$H_{eff}(Z) = \frac{G_F}{\sqrt{2}} U_{sb}\left[\bar{s}\gamma^\mu(1-\gamma_5)b\right]\left[\bar{\ell}\left(C_V^\ell\gamma_\mu - C_A^\ell\gamma_\mu\gamma_5\right)\ell\right], \qquad (6)$$

where C_V^ℓ and C_A^ℓ are the vector and axial vector $Z\ell^+\ell^-$ couplings and are given as

$$C_V^\ell = -\frac{1}{2} + 2\sin^2\theta_W \quad , \qquad C_A^\ell = -\frac{1}{2} \quad , \qquad (7)$$

where θ_W is the weak mixing (or Weinberg) angle [13].

The branching ratios for $\Lambda_b \to \Lambda e^+ e^-$ decay in the presence of Z-mediated FCNC are calculated in [2] as:

$$\mathrm{B}\left(\Lambda_b \to \Lambda e^+ e^-\right)_Z = 11.27 \times 10^{-6}. \qquad (8)$$

The same idea can be applied to a Z'-boson i.e., mixing among particles which have different Z' quantum numbers will induce FCNCs due to Z' exchange [14–16]. The flavor-changing coupling $U_{sb}^{Z'}$ is constrained by the process $b \to s\nu\bar{\nu}$ [17,18] and is found to be $\left|U_{sb}^{z'}\right| \frac{M_z^2}{M_{z'}^2} \le 7.1 \times 10^{-3}$. This can be turned into a bound on $U_{sb}^{Z'}$ if one assumes a value for $M_{Z'}$. If we assume $\left|U_{sb}^{Z'}\right| \sim \left|V_{tb} V_{ts}^*\right|$, then it is possible to write U_{sb} instead of $U_{sb}^{Z'}$, which gives significant contributions to the $\Lambda_b \to \Lambda e^+ e^-$ decay process. Thus the new contributions from Z'-boson are exactly in the similar manner as in the Z-boson. Therefore, we write the general effective Hamiltonian [14,15] that contribute to $\Lambda_b \to \Lambda \ell^+ \ell^-$ in the light of equation (6) as :

$$H_{eff}(Z') = \frac{G_F}{\sqrt{2}} U_{sb} \left[\bar{s} \gamma^\mu (1-\gamma_5) b \right] \left[\bar{\ell} \left(C_V^\ell \gamma_\mu - C_A^\ell \gamma_\mu \gamma_5 \right) \ell \right] \left(\frac{g'}{g} \frac{M_Z}{M_{Z'}} \right)^2, \quad (9)$$

where $g = e / \left(\sin\theta_W \cos\theta_W \right)$ and g' is the gauge coupling associated with the $U(1)'$ group. The net effective Hamiltonian can be written, from equations (6) and (9), as $H_{eff} = H_{eff}(Z) + H_{eff}(Z')$ and

$$H_{eff} = \frac{G_F}{\sqrt{2}} U_{sb} \left[\bar{s} \gamma^\mu (1-\gamma_5) b \right] \left[\bar{\ell} \left(C_V^\ell \gamma_\mu - C_A^\ell \gamma_\mu \gamma_5 \right) \ell \right] \left[1 + \left(\frac{g'}{g} \frac{M_Z}{M_{Z'}} \right)^2 \right], \quad (10)$$

and the corresponding branching ratio for the rare decay $\Lambda_b \to \Lambda e^+ e^-$ are calculated in the next section.

4. Results and Discussions

In this section, we calculate the branching ratio for the rare decay $\Lambda_b \to \Lambda e^+ e^-$ using recent data [10]: $m_e = \left(0.510998910 \pm 0.000000013 \right)$ MeV, $m_{\Lambda_b} = \left(5620.2 \pm 1.6\right)$ MeV, $m_\Lambda = \left(1115.683 \pm 0.006 \right)$ MeV, $\tau_{\Lambda_b} = \left(1.383^{+0.049}_{-0.048} \right) \times 10^{-12}$ s, $M_Z = \left(91.1876 \pm 0.0021\right)$ GeV, $G_F = \left(1.16637 \pm 0.00001 \right) \times 10^{-5}\, GeV^{-2}$, $\sin^2\theta_W = 0.23$ and $\left|U_{sb}\right| \cong 10^{-3}$ [12]. Since the Z' has not yet been discovered, its mass is unknown. However, the Z' mass is constrained by direct searches at Fermilab, weak neutral current data and precision studies at LEP and the SLC [19,20], which give a model-dependent lower bound around 500 GeV if the interaction is comparable to the other couplings of the standard model. In a study of *B* meson decays with Z'-mediated flavor-changing neutral currents [15], they study the Z'-boson in the mass range of a few hundred GeV to 1 TeV. Dittmar, Nicollerat and Djouadi [21] have studied Z' boson at LHC. They confirm that Z' bosons can be observed in the process $pp \to Z' \to \ell^+ \ell^-$ $(\ell = e, \mu)$, up to masses of about 5 TeV. In this paper, we study the Z'-boson in the mass range 500 GeV – 5 TeV.

In general, the value of g'/g is undetermined [22]. However, generically, one expects that $g'/g \approx 1$ if both U(1) groups have the same origin from some grand unified theory. We take $g'/g \approx 1$ in our calculations.

Table. branching ratio for $\boldsymbol{\Lambda_b \to \Lambda e^+ e^-}$ decay in z′ model

Mass of Z' boson (GeV)	Decays	Branching ratio in Z+ Z' model	% of increment (in comparison to SM value) due to the contribution of Z' boson
500	$\Lambda_b \to \Lambda e^+ e^-$	12.03×10^{-6}	16.52 %
5000	$\Lambda_b \to \Lambda e^+ e^-$	11.28×10^{-6}	0.21%

From the table, it is clear that depending on the precise value of $M_{Z'}$, the Z'-mediated FCNCs gives sizable contributions to $\Lambda_b \to \Lambda e^+ e^-$ decay process. Our estimated branching ratio for $\Lambda_b \to \Lambda e^+ e^-$ decay process is reasonably enhanced from its SM value [equation (5)]. Hence, the $\Lambda_b \to \Lambda e^+ e^-$ decay process could provide signals for new physics beyond the standard model. These facts lead to enrichment in the phenomenology of both the Z and Z'-mediated FCNCs and $\Lambda_b \to \Lambda e^+ e^-$ decay; and the physics beyond the standard model will be known after the discovery of the Z'-boson which is expected at the LHC.

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