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Study of $B_{s,d} \to \ell^+\ell^- \, (\ell = e, \mu, \tau)$ rare decays in Z' model

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Abstract: We discuss the rare decays $B_{s,d} \to \ell^+\ell^- \left(\ell = e, \mu, \tau \right)$ decays in a non-universal Z' model derived from extension of the standard model (SM).Considering the effect of Z'-mediated flavor changing neutral current (FCNC) we calculate the branching ratiofor $B_{s,d} \to \ell^+\ell^-$ decay processes. We compare the obtained results with predictions of the SM and discuss the sensitivity of theZ' boson mediated FCNCs in such rare decays.We find the branching ratios in Z' model scenario deviates from SM predictions. These discriminations between Z' boson effects and SM results provides clue for the presence of new physics (NP) beyond the scope of the SM.

Keywords : B mesons, Z' boson, Models beyond the standard model

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1. Introduction

The rare decays $B_{s,d} \to \ell^+\ell^- \left(\ell = e, \mu, \tau \right)$[1-4] which are predicted to be rare with in the SM involve several observables which can be cleanly interpreted from theoretical and experimental viewpoint.These rare B-meson decays presents vital base to analyse the flavour sector of the SM and also had become potential source to dig out possible signatures of new physics (NP) beyond the SM. $B_{s,d} \to \ell^+\ell^-$decays involve $b \to s(d)\ell^+\ell^-$ quark level transitions.In recent picture several observables of rare B-meson decays undergoing $b \to s(d)\ell^+\ell^-$ transitions show intriguing pattern of deviations from the SM predictions.Few of the examples of such discrepancy are: observation of deviation from the SM expectation in the angular observable P_5' [5-9] of $B \to K^*\mu^+\mu^-$ mode, observation of 2.6 σ deviation in $R_K = BR(B^+ \to K^+\mu^+\mu^-)/BR(B^+ \to K^+e^+e^-)$ in the $q^2 \in [1,6]\,\mathrm{GeV}^2$ bin [10], discrepancy in the differential branching fraction of the $B \to K^*\mu^+\mu^-$ processes [11] by the LHCb experiment, the observation of 3.2σ deviation in thedecay rate of the $B_s \to \phi\mu^+\mu^-$ [12] process and the recent measurement of $R_K^* = BR(B \to K^*\mu^+\mu^-)/BR(B \to K^*e^+e^-)$ [13] has added to the list of anomalies with the SM predictions. Though these deviations are not sufficient to prove the presence of NP effects but these data have intimated several anomalies in B-meson decays induced by FCNC processes which demands NP models as well as model independent way to explain the source of these anomalies vigorously.These transitions can occurs only at loop level and are predicted to be rare within the SM. The rare B-meson decays can accommodate the possibilities of physics beyond the SM due to several reasons: (i) They occur through one-loop diagrams and can provide useful information about heavy quarks in the loop. (ii) Since in these processes the decaying *b* quark is heavy, short-distance effects dominate over the long-distance effects and so these processes can be computed theoretically with high level accuracy. (iii) These decays are highly suppressed by loop and helicity factors with in the SM. If we consider non-SM particles in the loop processes or non-SM coupling mechanisms the rate of these decays can significantly change. We step forward in this direction and study $B_{s,d} \to \ell^+\ell^-$ decays in a Z' model [14] which arise in many extended SM scenarios having larger gauge symmetry group than the SM. Since the Z' has not yet been discovered, its exact mass is unknown. However, the Z' mass is constrained by direct searches at different colliders and by many theoretical models. In a study of B-meson decays with Z'-mediated FCNCs [15], they study the Z' boson in the mass range of a few hundred GeV to 1 TeV. Oda et al. [16] have predicted an upper bound on Z' boson mass, $M_{Z'} \leq 6$ TeV in classically conformal $U(1)'$ extended standard model.Recently, the CMS collaboration [17] has searched leptophobic Z' bosons decaying into four-lepton final states in proton-proton collisions $\sqrt{s}$ = 8 TeV and obtained the lower limit on the Z' boson mass as 2.5 TeV.

This paper is structured as follows: in Section 2, we first discuss the $B_{s,d} \to \ell^+\ell^-$ decays in the SM, and then we study it in the Z' model. In Section

3, we evaluate the branching ratio for $B_{s,d} \to \ell^+\ell^-$ decays considering the Z' bosons mediated FCNCs and give a comparative study between the SM result and our calculation.Finally, we present our conclusions in Section 4.

2. $B_{s,d} \to \ell^+\ell^-$ decays in the SM and Z' model

$B_{s,d} \to \ell^+\ell^- \left(\ell = e, \mu , \tau \right)$ processes are loop-suppressed with in the SM. But, they are potentially sensitive to probe the dilemma of NP contributions. The effective Hamiltonian [2] describing the $B_{s,d} \to \ell^+\ell^-$ processes is

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

where G_F is the Fermi coupling constant, $\lambda_t = V_{tb}V_{ts}^*$, $P_{R,L} = \frac{1}{2}\left(1 \pm \gamma_5\right)$, $p = p_+ + p_-$ the sum of the momenta of the ℓ^+ and ℓ^-, and C_7, C_9^{eff} and C_{10} are Wilson coefficients [18-22] evaluated at the b quark mass scale.We use the Vacuum Insertion Method (VIM) [23] for the evaluation of matrix elements. We can write the transition amplitude for this process as

$$M\left(B_{s,d} \to \ell^+\ell^-\right) = i\,\frac{G_F\,\alpha}{\sqrt{2}\,\pi}\,\lambda_t\; f_{B_{s,d}} C_{10}\, m_\ell \left(\bar{\ell}\gamma_5\ell\right)\;, \tag{2}$$

and the corresponding branching ratio [2] is given by

$$B\left(B_{s,d} \to \ell^+\ell^-\right) = \frac{G_F^2\,\tau_{B_{s,d}}}{16\pi^3}\,\alpha^2 f_{B_{s,d}}^2\; m_{B_{s,d}}\; m_\ell^2 \left|V_{tb}\,V_{ts(d)}^*\right|^2 C_{10}^2 \sqrt{1 - \frac{4m_\ell^2}{m_{B_{s,d}}^2}}\,. \tag{3}$$

Now considering the $B_{s,d} \to \ell^+\ell^-$ decay in the presence of Z-mediated FCNC [24-26] at tree level. The $Zbs(d)$ FCNC coupling, which affects B-decays, is parameterized by independent parameter U_{sb}. Hence, considering the Z boson contribution we can write the effective Hamiltonian [2] as:

$$H_{eff}(Z) = \frac{G_F}{\sqrt{2}}U_{sb}\left[\bar{q}\gamma^\mu\left(1-\gamma_5\right)b\right]\left[\bar{\ell}\left(C_V^\ell\,\gamma_\mu - C_A^\ell\,\gamma_\mu\gamma_5\right)\ell\right], \tag{4}$$

where C_V^{ℓ} and C_A^{ℓ} are the vector and axial vector $Z\ell^+\ell^-$ couplings. The corresponding branching ratio is given as

$$B\left(B_{s,d} \to \ell^+\ell^-\right)_Z = \frac{G_F^2\,\tau_{B_{,ds}}}{4\pi}\left|U_{sb}\right|^2 f_{B_{s,d}}^2\, m_{B_{s,d}}\, m_\ell^2 \left|C_A^{\ell}\right|^2 \sqrt{1-\frac{4m_\ell^2}{m_{B_{s,d}}^2}} \qquad (5)$$

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 and these effects can be as large as Z-mediated FCNCs. The new contributions from Z' boson have similar effect as from the Z boson. Therefore, we write the general effective Hamiltonian that contributes to $B_{s,d} \to \ell^+\ell^-$, in the light of equation (4) as :

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

where g and g' are the gauge coupling associated with the*U(1)* and$U(1)'$ group respectively. The net effective Hamiltonian can be writtenas $H_{eff} = H_{eff}(Z) + H_{eff}(Z')$ which is nothing but

$$H_{eff} = \frac{G_F}{\sqrt{2}}U_{sb}\left[\bar{q}\gamma^\mu(1-\gamma_5)b\right]\left[\bar{\ell}\left(C_V^{\ell}\,\gamma_\mu - C_A^{\ell}\,\gamma_\mu\gamma_5\right)\ell\right]\left[1+\left(\frac{g'}{g}\frac{M_Z}{M_{Z'}}\right)^2\right], \quad (7)$$

and the corresponding branching ratio is given as

$$B\left(B_{s,d} \to \ell^+\ell^-\right)_{Z+Z'} = \frac{G_F^2\,\tau_{B_q}}{4\pi}\left|U_{sb}\right|^2 f_{B_q}^2\, m_{B_q}\, m_\ell^2 \left|C_A^{\ell}\right|^2 \sqrt{1-\frac{4m_\ell^2}{m_{B_q}^2}} \left[1+\left(\frac{g'}{g}\frac{M_Z}{M_{Z'}}\right)^2\right]^2 \qquad (8)$$

This formula can be used for the calculation of branching ratio for the rare decays $B_{s,d} \to \ell^+\ell^-$.

4. Results and Discussion

In this section, we calculate the branching ratio for $B_{s,d} \to \ell^+\ell^-$ $\left(\ell = e, \mu, \tau\right)$ decay process using equation (8) and all the recent data from particle data group [27]. Our calculated results along with the SM values are encapsulated in Table-1. Since, the Z' boson is not discovered any of the collider experiments so far, its exact mass is not known. However there are several theoretical as well as experimental limits are imposed over the mass of Z' boson. Few of the references are discussed in the introduction section of this paper. So we have considered wide range for the mass of Z' boson from 100 GeV to 6TeV. We find that the branching ratios are increased from their corresponding SM values [28]. In our calculation we see that depending on the precise value of $M_{Z'}$, Z'-mediated FCNCs give sizable contributions to $B_{s,d} \to \ell^+\ell^-$ decays. Lower is the mass of Z' boson, more is the contribution towards the branching ratio.

Table-1

Decay	**BR in SM**[28]	**BR in Z' model**
$B_s \to e^+e^-$	$\left(8.54 \pm 0.55\right)\times 10^{-14}$	$\left(3.0491 - 0.7993\right)\times 10^{-13}$
$B_d \to e^+e^-$	$\left(2.48 \pm 0.21\right)\times 10^{-15}$	$\left(9.0233 - 2.2710\right)\times 10^{-15}$
$B_s \to \mu^+\mu^-$	$\left(3.65 \pm 0.23\right)\times 10^{-9}$	$\left(1.3015 - 0.3421\right)\times 10^{-8}$
$B_d \to \mu^+\mu^-$	$\left(1.06 \pm 0.09\right)\times 10^{-10}$	$\left(4.5044 - 1.9713\right)\times 10^{-10}$
$B_s \to \tau^+\tau^-$	$7.7 - 8.0 \times 10^{-7}$	$\left(2.6835 - 0.8700\right)\times 10^{-6}$
$B_d \to \tau^+\tau^-$	$\left(2.22 \pm 0.04\right)\times 10^{-8}$	$\left(7.5809 - 2.1810\right)\times 10^{-8}$

4. Conclusion

The $B_{s,d} \to \ell^+\ell^-$ rare decays play an important role in the SM and their study is relevant to indirect searches for physics beyond the SM. These decays can provide an excellent environment for giving complimentary information on the semileptonic $b \to (s,d)\,\ell^+\ell^-$ operators. These decays are already studied by several authors [29-34]In this paper, we study the effect of Z'-mediated FCNCs on these decays. We have found that although there is no noticeable difference in the branching ratios for $B_{s,d} \to \ell^+\ell^-$ decays between the SM values and the values in Z' model.Hence, the FCNC processes play integral part for searching NP effects in B-meson decays. We expect these rare decays provide very useful tool for affording new tests of lepton universality and to explore new physics beyond the SM.

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