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PARTICLES AND FIELDS

Search for the $B_s^0 \rightarrow e^+e^-$ and $B_d^0 \rightarrow e^+e^-$ Decays in Flavor-Changing Z' Model

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Abstract The precise prediction of the branching ratios of the very rare decays $B_s^0 \rightarrow e^+e^-$ and $B_d^0 \rightarrow e^+e^-$ is an important ingredient for high energy research beyond standard model (SM). Recently, the CDF collaboration has reported upper limits for the branching ratios $B(B_s^0 \rightarrow e^+e^-) < 2.8 \times 10^{-7}$ and $B(B_d^0 \rightarrow e^+e^-) < 8.3 \times 10^{-8}$ at 90 % confidence level. These branching ratios are approximately seven orders of magnitude larger than the SM predictions, providing in this way a direction in which the SM could be extended. In this paper, the $B_s^0 \rightarrow e^+e^-$ and $B_d^0 \rightarrow e^+e^-$ rare decays in flavor-changing Z' model are studied. Our estimated branching ratios are enhanced from their SM values and provide signals for new physics.

Keywords B mesons · Neutral currents · Models beyond the standard model · Z' boson

1 Introduction

The study of rare decays of B mesons involving flavor-changing neutral current (FCNC) has been a topic of great interest for long. They are sensitive to probe the flavor sector of the standard model (SM) and can be computed theoretically to an exceptionally high degree of precision. In particular, the decay modes $B_{s,d}^0 \rightarrow \ell^+\ell^-$ ($\ell = e, \mu, \tau$) have received considerable interest in recent years [1–18] due to several reasons: (i) They occur through one-loop diagrams and can provide useful information about heavy quarks in the loop [19]. (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. Therefore, their branching ratios are small in the SM. If we consider non-SM particles in the loop processes or non-SM coupling mechanisms (e.g., minimal supersymmetric standard model (MSSM), littlest Higgs model, flavor-changing Z' models, etc.), the rate of these decays can significantly change. Hence, the corresponding branching ratios would be different from their SM values and provide signals of new physics beyond the SM. For example, in two-Higgs doublet models, the corresponding branching ratios can be strongly enhanced due to additional diagrams involving the Higgs boson [19–21]. In some models with Z-mediated FCNCs, the corresponding branching ratios can be enhanced two orders of magnitude over those of their SM values [22, 23]. In the MSSM, the branching ratio of the decay $B_s^0 \rightarrow \mu^+\mu^-$ is proportional to the sixth power of tan β (the ratio of vacuum expectation values of the neutral components of the two Higgs fields) [24]. Furthermore, in the Littlest Higgs (LH) model with T--parity [25] the branching ratio $B(B_s^0 \rightarrow \mu^+\mu^-)$ is found to be larger than its SM value and it can be enhanced by 30 %. But in the branching ratio $B(B_d^0 \rightarrow \mu^+\mu^-)$, the enhancement can be larger and also suppression is possible. The enhancement or suppression of the branching ratio is an indication for new physics (NP). The values of the branching ratios for these decays in the standard model are predicted as [26]: $B(B_s^0 \rightarrow \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$ and $B(B_d^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$. Recently, the CMS collaboration [27], LHCb collaboration [28], and the combined CMS and LHCb collaboration [29] have measured the branching ratios $B($

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$B_s^0 \to \mu^+\mu^-$) and $B(B_d^0 \to \mu^+\mu^-)$. Their combined measurements [29] give these branching ratios as: $B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ and $B(B_d^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$, where the uncertainties include both statistical and systematic sources. Recently, the CDF collaboration [2] has reported the upper limits for these branching ratios as: $B(B_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$ and $B(B_d^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$ at 95 % CL. Recently, we [30] have studied these decays in flavor-changing Z' model with varying the mass of Z' boson in the range of 500 GeV–5 TeV. Our estimation gives the branching ratio values in the range of $B(B_s^0 \to \mu^+\mu^-) = (3.51 \pm 0.01) \times 10^{-9}$–$(4.87 \pm 0.16) \times 10^{-9}$ and $B(B_d^0 \to \mu^+\mu^-) = (1.17 \pm 0.04) \times 10^{-10}$–$(1.50 \pm 0.12) \times 10^{-10}$. Our estimated values of the branching ratios are enhanced from their SM values and provide signals for new physics. Our estimated branching ratio $B(B_s^0 \to \mu^+\mu^-)$ is greater than and $B(B_d^0 \to \mu^+\mu^-)$ is smaller than the recent combined CMS and LHCb measurements. Again, our estimated values of the branching ratios satisfy the experimental upper limits predicted by the CDF collaboration.

Since the decay width is approximately proportional to the lepton mass squared, the decays $B_{s,d}^0 \to e^+e^-$ are further suppressed in comparison to the decays $B_{s,d}^0 \to \mu^+\mu^-$ by $(m_e/m_\mu)^2$. In the SM, the branching ratios for these decays are predicted as [7]: $B(B_s^0 \to e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}$ and $B(B_d^0 \to e^+e^-) = (2.48 \pm 0.21) \times 10^{-15}$. These rates put them beyond the reach of current experiments. In 2005, Alok and Uma Sankar [17] have shown that if future experiments measure $B_s^0 \to \ell^+\ell^-$ ($\ell = e, \mu$) with a branching ratio greater than 10^{-8} then the new physics responsible for this decay must be of scalar/pseudoscalar type. Recently, the CDF collaboration [3] has predicted their upper limits at 90 % confidence level as $B(B_s^0 \to e^+e^-) < 2.8 \times 10^{-7}$ and $B(B_d^0 \to e^+e^-) < 8.3 \times 10^{-8}$. The difference in the observed branching ratios with respect to the SM predictions would provide a direction in which the SM should be extended. That is why in this paper, we are interested to search for $B_{s,d}^0 \to e^+e^-$ decays in the flavor-changing Z' model.

Z' gauge bosons are predicted theoretically in many extensions of the SM [31–33] such as grand unified theories (GUTs), left-right symmetric models, Little Higgs models, and superstring theories. It is surprising that a Z' boson is predicted at the weak scale [33] in supersymmetric E_6 models. However, there are stringent limits on the mass of an extra Z' from the non-observation of direct production followed by decays into e^+e^- or $\mu^+\mu^-$ by CDF [34], while indirect constraints from the precision data also limit the Z' mass (weak neutral current processes and LEP II) and severely constrain the $Z-Z'$ mixing angle θ [35, 36]. These limits are model-dependent but are typically in the range $M_{Z'} \geq 500$ GeV and $|\theta| \leq 10^{-3}$ for standard GUT models. Our [37] estimation of the mass of the Z' boson from $B_q^0 - \overline{B_q^0}$ mixing lies in the range of 1352–1665 GeV. Recently, the ATLAS collaboration [38] sets the lower mass limits for the sequential standard model (SSM) Z'_{SSM} as 2.90 TeV, for Z'_ψ as 2.51 TeV and for Z'_χ as 2.62 TeV.

In the Z' sector, there has been a great deal of investigation to understand the underlying physics beyond the SM [39]. It has been shown that a leptophobic Z' boson can appear in E_6 gauge models due to mixing of gauge kinetic terms [40, 41]. Flavor mixing can be induced at the tree level in the up-type and/or down-type quark sector after diagonalizing their mass matrices. Mixing between ordinary and exotic left-handed quarks induces Z-mediated FCNCs. The right-handed quarks d_R, s_R and b_R have different $U(1)'$ quantum numbers than exotic q_R and their mixing will induce Z'-mediated FCNCs [40, 42] among the ordinary down quark types. Tree level FCNC interactions can also be induced $B_d^0 \to e^+e^-$ by an additional Z' boson on the up-type quark sector [43]. In the Z' model [44], the FCNC $b-s(d)-Z'$ 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 the electronic decay of the B_s^0 and B_d^0. With FCNCs, the Z' boson contributes at tree level, and its contribution will interfere with the SM contributions [42, 45].

This paper is organized as follows: in Section 2, we discuss the $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays in the SM and recent experimental results for their branching ratios. In Section 3, we give a brief account of the flavor-changing Z' model and evaluate the branching ratio for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays. In Section 4, we discuss the results, so obtained, and compare them with those of others.

2 $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ Decays in the Standard Model

The B_s^0 and B_d^0 mesons are unstable particles that decay via the weak interaction. The $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays are loop-suppressed in the SM. However, these decays are potentially sensitive to new physics beyond the SM. These decays involve $b \to s$ and $b \to d$ transitions, respectively. In the SM, these decays occur through weak interaction whose amplitudes are suppressed via Glashow-Iliopoulos-Maiani mechanism [46]. The SM expression for the branching ratio of $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays can be written as [47]:

$$B\left(B_s^0 \to e^+e^-\right) = \frac{G_F^2}{\pi}\left[\frac{\alpha}{4\pi \sin^2\theta_W}\right]^2 \tau_{B_s} f_{B_s}^2 m_e^2 m_{B_s} \sqrt{1 - \frac{4m_e^2}{m_{B_s}^2}} \left|V_{tb}^* V_{ts}\right|^2 Y^2(x_t) \tag{1}$$

and

$$B\left(B_d^0 \to e^+e^-\right) = \frac{G_F^2}{\pi}\left[\frac{\alpha}{4\pi \sin^2\theta_W}\right]^2 \tau_{B_d} f_{B_d}^2 m_e^2 m_{B_d} \sqrt{1 - \frac{4m_e^2}{m_{B_d}^2}} \left|V_{tb}^* V_{td}\right|^2 Y^2(x_t) \tag{2}$$

where $Y(x_t) = Y\left(\frac{m_t^2}{M_W^2}\right)$ is an appropriate loop function, consists of Z-penguin and box diagram contributions, including QCD corrections as well as the leading electroweak corrections. The values of the branching ratio for these decays in the standard model are predicted as [7]:

$$B\left(B_s^0 \to e^+e^-\right) = (8.54 \pm 0.55) \times 10^{-14} \tag{3}$$

$$B\left(B_d^0 \to e^+e^-\right) = (2.48 \pm 0.21) \times 10^{-15} \tag{4}$$

Recently, the CDF collaboration [3] has searched for the $B_s^0 \to e^+e^-$, $B_d^0 \to e^+e^-$ decays and obtained the upper limits of branching ratios as

$$B\left(B_s^0 \to e^+e^-\right) < 2.8 \times 10^{-7}$$
$$B\left(B_d^0 \to e^+e^-\right) < 8.3 \times 10^{-8} \tag{5}$$

These branching ratios are approximately seven orders of magnitude larger than the standard model (SM) predictions. These differences in the observed branching ratios with respect to the SM predictions would provide a direction in which the SM should be extended.

3 $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ Decays in Z' Model

We consider a model (as given in [44, 48]) with an extra $U(1)'$ gauge symmetry. The Z' boson is associated with the additional $U(1)'$ gauge symmetry. Generally, a model with an extra $U(1)'$ gauge symmetry is characterized by the $U(1)'$ gauge coupling, chiral charges of the matter fields, the mass of Z' boson, and possible mixing angle between Z and Z' boson [49]. Here, we have assumed that there is no mixing between Z and Z' boson. The current associated with the $U(1)'$ gauge symmetry is [44]:

$$J_\mu = \sum_{i,j} \overline{\psi}_i \gamma_\mu \left[\in_{\psi L_{i,j}} P_L + \in_{\psi R_{i,j}} P_R\right] \psi_j \tag{6}$$

where the sum extends over all quarks and leptons $\psi_{i,j}$, $P_{R,L}=(1+\gamma_5)/2$, and $\in_{\psi L,R_{i,j}}$ denote the chiral coupling of Z' with fermions. It is assumed that the Z' couplings to the leptons and up-type quarks are flavor-diagonal and family-universal, i.e., $\in^u_{L,R}=Q^u_{L,R}1$, $\in^e_{L,R}=Q^e_{L,R}1$, and $\in^\nu_L=Q^\nu_L 1$, where 1 is the 3 × 3 identity matrix and $Q^u_{L,R}$, $Q^e_{L,R}$, and Q^ν_L are the chiral charges.

The interaction of Z' with the down-type quarks is:

$$L_{NC} = -g' Z'_\mu \left(\overline{d}, \overline{s}, \overline{b}\right)_I \gamma^\mu \left(\in^d_L P_L + \in^d_R P_R\right) \begin{pmatrix} d \\ s \\ b \end{pmatrix}_I \tag{7}$$

where g' is the gauge coupling associated with the $U(1)'$ group and the subscript I denotes the interaction basis. It is assumed that

$$\in^d_L = Q^d_L \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & x \end{pmatrix} \quad , \quad \in^d_R = Q^d_R \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

If the $\in$ are nondiagonal matrices, FCNCs are induced [48]. Furthermore, if the Z' couplings are diagonal but nonuniversal, flavor changing couplings are induced by fermion mixing. The magnitude of Z'-mediated FCNC can be known by evaluating the parameter x, where x represents the strength of Z' coupling to the third-generation LH quarks relative to the first two generations. The effects would vanish for x=1.

In this model, the branching ratio of $B_s^0 \to e^+e^-$ decay can be written as

$$B\left(B_s^0 \to e^+e^-\right) = \frac{G_F^2}{4\pi} \tau_{B_s} f_{B_s}^2 m_e^2 m_{B_s} \sqrt{1 - \frac{4m_e^2}{m_{B_s}^2}} \left|V_{tb}^* V_{ts}\right|^2$$
$$\times \left[\left|\frac{\alpha}{2\pi \sin^2\theta_W} Y\left(\frac{m_t^2}{M_W^2}\right) + 2\frac{\rho_L^{bs}\rho_L^{ee}}{V_{tb}^* V_{ts}}\right|^2 + \left|2\frac{\rho_L^{bs}\rho_R^{ee}}{V_{tb}^* V_{ts}}\right|^2\right] \tag{9}$$

where

$$\rho_{L,R}^{ee} = \frac{g' M_Z}{g M_{Z'}} Q_{L,R}^e \tag{10}$$

where $g= e/(\sin\theta_W \cos\theta_W)$ and g' is the gauge coupling associated with the $U(1)'$ group. Similarly, the branching ratio of $B_d^0 \to e^+e^-$ decay can be written as:

$$B\left(B_d^0 \to e^+e^-\right) = \frac{G_F^2}{4\pi} \tau_{B_d} f_{B_d}^2 m_e^2 m_{B_d} \sqrt{1 - \frac{4m_e^2}{m_{B_d}^2}} \left|V_{tb}^* V_{td}\right|^2$$
$$\times \left[\left|\frac{\alpha}{2\pi \sin^2\theta_W} Y\left(\frac{m_t^2}{M_W^2}\right) + 2\frac{\rho_L^{bd}\rho_L^{ee}}{V_{tb}^* V_{td}}\right|^2 + \left|2\frac{\rho_L^{bd}\rho_R^{ee}}{V_{tb}^* V_{td}}\right|^2\right] \tag{11}$$

We use Eqs. (9) and (11) for the calculation of branching ratio for the rare decays $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ in the next section.

4 Results and Discussions

In this section, we calculate the branching ratio for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays using all the recent data from PDG [50]: m_e=0.51 MeV, $m_{B_s} = 5.36677 \pm 0.00024$ GeV, $m_{B_d} = 5.27958 \pm 0.00017$ GeV, average lifetime $\tau_{B_s} = (1.497 \pm 0.015) \times 10^{-12} s$, $\tau_{B_d} = (1.519 \pm 0.007) \times 10^{-12} s$, decay constant $f_{B_s} = 0.227$ GeV, $f_{B_d} = 0.190$ GeV, M_Z= 91.1876 GeV, G_F=1.16638 × 10^{-5} GeV^{-2}, $\sin^2\theta_W$=0.23, α=1/127.937, M_W=80.385 GeV, m_t=173.2 GeV, $|V_{tb}^* V_{ts}|$= 0.0405 and $|V_{tb}^* V_{td}|$=0.0087. Since the Z' has not yet been discovered, its mass is unknown. However, the Z' mass is

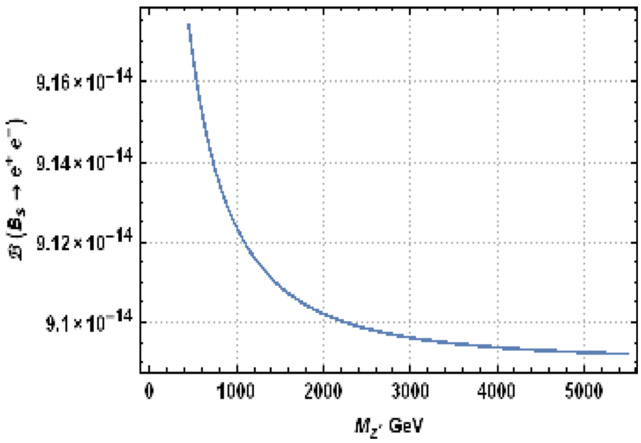

Fig. 1 The variation of branching ratio $B(B_s^0 \to e^+e^-)$ with the mass of Z' boson

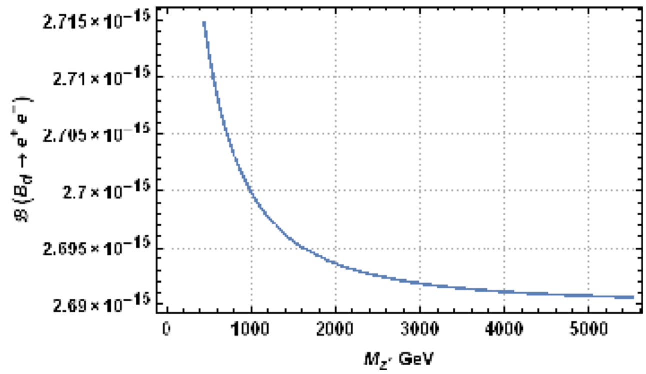

Fig. 2 The variation of branching ratio $B(B_d^0 \to e^+e^-)$ with the mass of Z' boson

constrained by direct searches at Fermilab, weak neutral current data and precision studies at LEP and the SLC [34, 36], which give a model-dependent lower bound around 500 GeV. In a study of B meson decays with Z'-mediated flavor-changing neutral currents [51], they study the Z' boson in the mass range of a few hundred GeV to 1 TeV. Our [37] estimation of Z' boson mass from B_q^0–$\overline{B_q^0}$ mixing lies in the range of 1352–1665 GeV. Recently, the ATLAS collaboration [38] sets the lower mass limits for the sequential standard model (SSM), Z'_{SSM} as 2.90 TeV, for Z'_ψ as 2.51 TeV, and for Z'_χ as 2.62 TeV. Recently, Oda et al. [52] have found an upper bound on Z' boson mass, $M_{Z'} \leq$ 6 TeV in classically conformal $U(1)'$ extended standard model. We hope the Z' boson in this mass range would be discovered at the LHC Run–2 in the near future. In our work, we have used the lower limit of $M_{Z'}$ =500 GeV and upper limit $M_{Z'}$ =6 TeV for our calculations.

In general, the value of g'/g is undetermined [53]. 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.

Using the lower limit for the mass of Z' boson, $M_{Z'}$ = 500 GeV, we get

$$B\left(B_s^0 \to e^+e^-\right) = (9.13 \pm 0.27) \times 10^{-14} \tag{12}$$

$$B\left(B_d^0 \to e^+e^-\right) = (2.72 \pm 0.07) \times 10^{-15} \tag{13}$$

Again, using the mass of Z' boson, $M_{Z'}$ =6000 GeV, we get

$$B\left(B_s^0 \to e^+e^-\right) = (9.01 \pm 0.11) \times 10^{-14} \tag{14}$$

$$B\left(B_d^0 \to e^+e^-\right) = (2.62 \pm 0.10) \times 10^{-15} \tag{15}$$

For other intermediate values of $M_{Z'}$, one can get the corresponding value of branching ratios. The variation of branching ratio for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays with $M_{Z'}$ is shown in Figs. 1 and 2, respectively. From the figures, it is clear that depending on the precise value of $M_{Z'}$, Z'-mediated FCNCs give sizable contributions to both $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays. The lower is the mass of Z' boson, the more is the contribution toward the branching ratio. Thus, our estimation gives the values of the branching ratio for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays in the range of $B(B_s^0 \to e^+e^-)=(9.01 \pm 0.11)\times 10^{-14}$–$(9.13 \pm 0.27)\times 10^{-14}$, and

$$\begin{aligned} B\left(B_d^0 \to e^+e^-\right) &= (2.62 \pm 0.10) \\ &\quad \times 10^{-15} - (2.72 \pm 0.07) \\ &\quad \times 10^{-15} \end{aligned} \tag{16}$$

From Eq. (16), it is clear that our estimated branching ratios for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$ decays are enhanced from their SM values [Eqs. (3) and (4)] due to the effect of Z'-mediated FCNCs. Our estimated branching ratios $B(B_s^0 \to e^+e^-)$ and $B(B_d^0 \to e^+e^-)$ satisfy the recent CDF collaboration [3] upper limits (Eq. (5)). Again, our estimated branching ratio $B(B_d^0 \to e^+e^-)$ also satisfies the experimental upper limits predicted at 90 % CL by CLEO collaboration [$B(B_d^0 \to e^+e^-) <$ 8.3 × 10^{-7}] [54] and the BELLE collaboration [$B(B_d^0 \to e^+e^-) <$1.9 × 10^{-7}] [55]. These facts lead to enrichment in the phenomenology of Z'-mediated FCNCs. The recent experimental upper bounds on the branching ratios $B(B_s^0 \to e^+e^-)$ and $B(B_d^0 \to e^+e^-)$ are almost seven orders of magnitude greater than the SM prediction. Therefore, we expect these rare decays provide very sensitive probe of new physics beyond the SM. If these branching ratios are measured in the near future, their precise measurement would constrain the allowed range of the mass of the Z' boson. We are looking forward to a precise measurement of these branching ratios at the LHC Run-2 or any of the future colliders. Furthermore, the improved theory accuracy is also essential for interpreting the experimental findings in terms of the SM or new physics. This challenge can be confronted by both theory and experiment in collaboration.

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