Indian Journal of Pure & Applied Physics
Vol. 57, September 2019, pp. 652-654

Study of semileptonic decay $B \to \rho l^+ l^-$ in non-universal Z' model

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Received 3 July 2019

Exclusive B decays based on $b \to s(d)$ transition provide useful information about the various parameters in the standard model (SM) and also offer a great possibility for searching the new physics (NP). Although, there exists a lot of precise results on $b \to s l^+ l^-$ induced processes, there is lack of sufficient data for $b \to d l^+ l^-$ induced decays. From experimental evidences it is found that the B meson decays which have the quark level transition $b \to d$ have small branching ratio $\mathcal{O}(10^{-8})$ and large CP asymmetry. So, B meson decays induced by $b \to d$ flavour changing neutral current (FCNC) transitions are very challenging to probe the quark-flavour sector of the standard model (SM) and also to search NP. To the best of our knowledge, the decay mode $B \to \rho l^+ l^-$ $(l = \tau, \mu, e)$ has not been studied experimentally so far. In this work, we are interested to study theoretically $B \to \rho l^+ l^-$ decay which proceeds via $b \to d l^+ l^-$ transition at the quark level. We study the CP violation asymmetry in the exclusive decay channel $B \to \rho l^+ l^-$ in a non-universal Z' model. We find a significant deviation from the SM value of CP violation asymmetry for this decay which provides a clear conjecture for NP arising from Z' gauge boson.

Keywords: Decays of B mesons, Semileptonic decays, Flavour changing neutral currents, Models beyond the standard model

1 Introduction

In recent years, semileptonic decays of bottom hadrons are in the focus of many theoretical and experimental studies due to increasing experimental evidence of new physics (NP). Rare B meson decays which are induced by FCNC transition $b \to s(d)$ play one of the most important role in the research area of particle physics, especially in the flavour sector of standard model (SM). These decays occur at the loop level and generally are suppressed at the tree level in SM. Though there exists several data for $b \to s l^+ l^-$ processes but the detection of decays having $b \to d$ quark level of less branching ratio and large CP asymmetry. It is also found that the leading order contribution for $b \to d$ quark level transition is smaller than that of the transition $b \to s$. Hence, rare semileptonic B meson decays especially which are induced by $b \to d$ FCNC transition give a signal for NP beyond the SM. Here, we interested to study $B \to \rho l^+ l^-$ decays in non-universal Z' model. Non-universal Z' model is one of the most important theoretically constructed NP model beyond the SM[1-6].

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2 Standard Model Contribution

To the best of our knowledge, the decay mode $B \to \rho l^+ l^-$ $(l = \tau, \mu, e)$ has not been studied experimentally yet. In the exclusive rare decay channel $B \to \rho l^+ l^-$, the basic quark level process is $b \to d l^+ l^-$. In the SM, the effective hamiltonian for the transition $b \to d l^+ l^-$ is expressed as[7,8]:

$$H_{eff} = -\frac{4G_F \alpha}{\sqrt{2}} V_{tb} V_{td}^* \left[\sum_{i=1}^{10} C_i O_i - \lambda_u \{C_1 | O_1^u - O1 + C2O2u - O2, \quad \ldots (1)$$

where we have used the unitary condition for the CKM matrix as, $V_{tb}V_{td}^* + V_{ub}V_{ud}^* \approx -V_{cb}V_{cd}^*$ and $\lambda_u = \frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*}$. O_1 and O_2 are the current operators, $O_3 - O_6$ are QCD penguin operators and O_9, O_{10} are semileptonic electroweak penguin operators[7,9], G_F is Fermi coupling constant. The operators $\{O_i\}$ are given in literature[10,11] by replacing $s \to d$. Now from Eq. (1) the QCD corrected matrix element can be written as:

$$\mathcal{M} \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{td}^* \times \left\{-2C_7^{eff} \frac{m_b}{q^2} \left(\bar{d} i \sigma_{\mu\nu} q^\nu P_R b\right)\left(\bar{l} \gamma^\mu l\right) + C9eff d\gamma\mu PLbl\gamma\mu l + C10 d\gamma\mu PLbl\gamma\mu\gamma 5l, \quad \cdot \ldots (2)$$

Where, C_7^{eff}, C_{10} and C_9^{eff} are Wilson coefficients[8,12-16]. Now the matrix element of the decay $B \to \rho l^+ l^-$ in terms of form factors can be represented as follows[17]:

$$\mathcal{M}^{B\to\rho} = [i \in_{\mu\nu\alpha\beta} \epsilon^{\nu^*} p_B^{\beta} q^{\beta} A + \epsilon_{\mu}^{*} B + (\epsilon^{*} q)(p_B)_{\mu} C](\bar{l}\gamma^{\mu} l) + [i \in_{\mu\nu\alpha\beta} \epsilon^{\nu^*} p_B^{\alpha} q^{\beta} D + \epsilon_{\mu}^{*} E + (\epsilon^{*} q)(p_B)_{\mu} F](\bar{l}\gamma^{\mu} l) + H(\epsilon^{*} q)(\bar{l}\gamma_5 l) \quad \ldots (3)$$

In the above expression A, B, C, D, E, F and H are taken from literature[17] and they are represented in terms of form factors given in literature[18]. Now to obtain the expression of CP partial width asymmetry first we have to calculate the decay rate Γ and $\bar{\Gamma}$ which are associated with the decays $\bar{B} \to \rho l^{+} l^{-}$ and $\to \bar{\rho} l^{+} l^{-}$, respectively. The expressions of the differential decay rate for the decay channel $\bar{B} \to \rho l^{+} l^{-}$ and $B \to \bar{\rho} l^{+} l^{-}$ are represented by:

$$\frac{d\Gamma}{d\hat{s}} = \frac{{G_F}^2 {m_B}^5 \alpha^2}{3\times 2^{10}\times \pi^5} |V_{tb} V_{td}^{*}|^2 \lambda^{\frac{1}{2}}\left(1, \hat{s}, \hat{m}_{\rho}{}^2\right) \times \sqrt{1 - \frac{4\hat{m}_l{}^2}{\hat{s}}}\, \Sigma_{\rho} \quad \ldots (4)$$

$$\frac{d\bar{\Gamma}}{d\hat{s}} = \frac{{G_F}^2 {m_B}^5 \alpha^2}{3\times 2^{10}\times \pi^5} |V_{tb} V_{td}^{*}|^2 \lambda^{\frac{1}{2}}\left(1, \hat{s}, \hat{m}_{\rho}{}^2\right) \times \sqrt{1 - \frac{4\hat{m}_l{}^2}{\hat{s}}}\left(\Sigma_{\rho} + 4Im\lambda_u \Delta_{\rho}\right) \quad \ldots (5)$$

Where, Σ_{ρ} and Δ_{ρ} are given in literature[17]. From the definition of partial width CP asymmetry we can obtain the final expression of it in terms of Σ_{ρ} and Δ_{ρ} as:

$$A_{CP}(\hat{s}) = \frac{-2Im\lambda_u \Delta_{\rho}}{\Sigma_{\rho} + 2Im\lambda_u \Delta_{\rho}} \quad \ldots (6)$$

3 Contribution from FCNC Mediated Z' Boson

Now we will discuss the effect of FCNC mediated Z' boson on the partial width CP asymmetry of the semileptonic decay channel $B \to \rho l^{+} l^{-}$. One of the most precise extension of SM is an extra symmetry gauge group known as $U(1)'$ which introduces a neutral, massive gauge boson Z'. One fundamental feature of Z' model is that due to family non-universal couplings, Z' boson has flavour changing fermionic coupling at the tree level leading to important phenomenological indications. In non-universal Z' model, FCNC transition for $b \to d l^{+} l^{-}$ process occurs at the tree level due to the presence of non-diagonal chiral coupling matrix. The detail analysis of this model is discussed in literature[3]. By neglecting $Z - Z'$ mixing and considering the couplings of only right handed quarks with Z' are diagonal[19,20], we can write the new modified Z' part of effective hamiltonian for the transition $b \to d l^{+} l^{-}$ as:

$$H_{eff}^{Z'} = -\frac{2G_F}{\sqrt{2}\pi} V_{tb} V_{td}^{*} \left[\frac{B_{db}^{L} S_{ll}^{L}}{V_{tb} V_{td}^{*}} \bar{s}\gamma_{\mu} \times (1-\gamma_5) b \bar{l}\gamma^{\mu} (1-\gamma_5) l + \frac{B_{db}^{L} S_{ll}^{R}}{V_{tb} V_{td}^{*}} \bar{s}\gamma_{\mu} \times (1-\gamma_5) b \bar{l}\gamma^{\mu} \times (1+\gamma_5) l\right] \quad \ldots (7)$$

The contributions of Z' boson on the current operators, semileptonic electroweak penguin operators and QCD penguin operators remain same as that of the SM. Hence, the effective hamiltonian given in Eq. (7) can be summarized as follows:

$$H_{eff}^{Z'} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{td}^{*} \left[\wedge_{db} C_9^{Z'} O_9 + \wedge_{db} C_{10}^{Z'} O_{10}\right] \quad \ldots (8)$$

Where, $$\wedge_{db} = \frac{4\pi e^{-i\varphi_{db}}}{\alpha V_{tb} V_{td}^{*}}, \quad \ldots (9)$$

Here, $S_{LL} = S_{ll}^{L} + S_{ll}^{R}$ and $D_{LL} = S_{ll}^{L} - S_{ll}^{R}$. … (10)

Where, $B_{db}^{L} = \left|B_{db}^{L}\right| e^{-i\varphi_{db}}$ indicates the off-diagonal left handed couplings of quark sector with Z' boson and φ_{db} is the new weak phase. Now the total contributions on two Wilson coefficients C_9 and C_{10} can be written as:

$$C_9^{Total} = C_9^{eff} + \wedge_{db} C_9^{Z'} \quad \ldots (11)$$

$$C_{10}^{Total} = C_{10} + \wedge_{db} C_{10}^{Z'} \quad \ldots (12)$$

4 Results and Discussion

To evaluate these observables in Z' model, we have fixed the numerical values of the coupling parameter $|B_{db}|$ and the weak phase φ_{db}. These values are taken from literature[21,22] and encapsulated in Table 1 for two different scenarios S_1 and S_2. The numerical values of all input parameters are taken from literature[17, 23].

In Fig. 1(a) we find that for $\hat{s} = 0.7$, $A_{CP}(\hat{s})$ increases slowly and cross the SM value with increase in the coupling parameters S_{LL} and D_{LL} in $B \to \rho\tau^{+}\tau^{-}$ decay. This variation is significantly large for S_1. For S_2, $A_{CP}(\hat{s})$ touches the SM value at the higher value of coupling parameters. In Fig. 1(b and c), $A_{CP}(\hat{s})$ also increases slowly and crosses the SM value with the increase of Z' coupling

Table 1 — Numerical values of Z' coupling parameters and weak phase.

Scenarios	$B_{db} \times 10^{-3}$	φ_{db} in degree
S_1	0.16 ± 0.08	-33 ± 45
S_2	0.12 ± 0.03	-23 ± 21

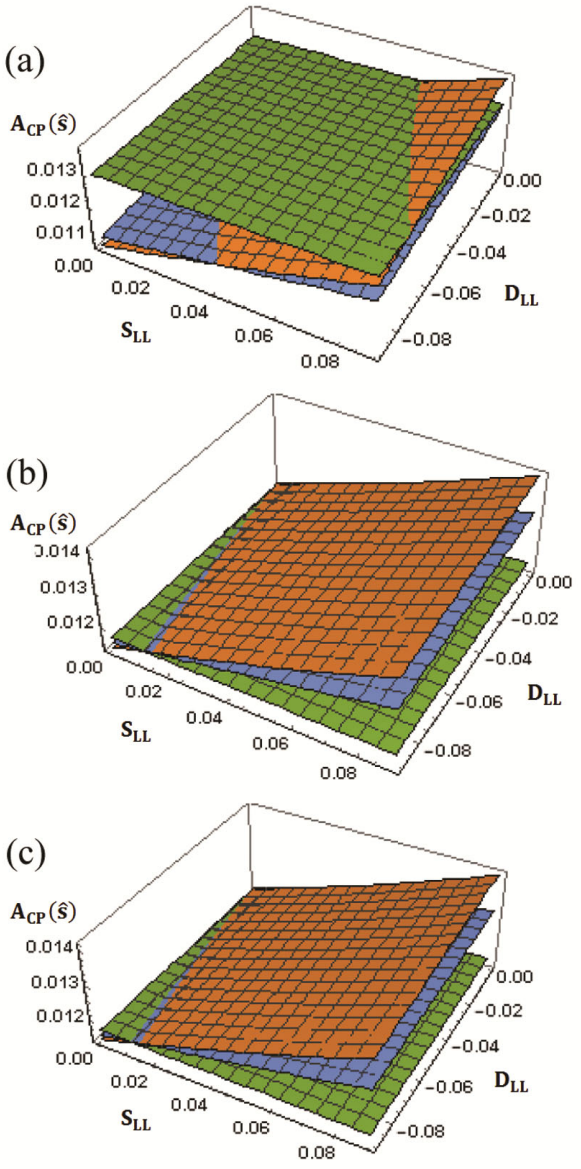

Fig. 1 — The dependence of CP violation asymmetry $A_{CP}(\hat{s})$ on coupling parameters S_{LL} and D_{LL} for the decays (a) $B \to \rho\tau^+\tau^-$, (b) $B \to \rho\mu^+\mu^-$ and (c) $B \to \rho e^+e^-$ for SM (green plate), scenario-1 (orange plate) and scenario-2 (blue plate).

parameters for $B \to \rho\mu^+\mu^-$ and $B \to \rho e^+e^-$ decays, respectively. This deviation of $A_{CP}(\hat{s})$ from the SM value provides a clue for NP. This may indicate the lepton flavour non-universality due to unequal enhancement of $A_{CP}(\hat{s})$ for $B \to \rho\tau^+\tau^-$, $B \to \rho\mu^+\mu^-$ and $B \to \rho e^+e^-$ decay modes.

Acknowledgment

P Nayek and S Sahoo would like to thank SERB, DST, Govt of India for financial support through grant no. EMR/2015/000817.

References

1 Hewett J & Rizzo T, *Phys Rep*, 183 (1989) 193.
2 Leike A, *Phys Rep*, 317 (1999) 143.
3 Langacker P & Plümacher M, *Phys Rev D*, 62 (2000) 013006.
4 Sahoo S, *Indian J Phys*, 80 (2006) 191.
5 Feldman D, Liu Z & Nath P, *Phys Rev Lett*, 97 (2006) 021801.
6 Langacker P, *Rev Mod Phys*, 81 (2009) 1199.
7 Buchalla G, Buras A & Lautenbacher M, *Rev Mod Phys*, 68 (1996) 1125.
8 Krüger F & Sehgal L M, *Phys Rev D*, 55 (1997) 2799.
9 Ali A, arXiv: hep-ph/9709507.
10 Grinstein B, Savage M J & Wise M B, *Nucl Phys B*, 319 (1945) 271.
11 Misiak M, *Nucl Phys B*, 393 (1993) 23.
12 Xiong Z & Yang J M, *Nucl Phys B*, 628 (2002) 193.
13 Cho P L, Misiak M & Wyler D, *Phys Rev D*, 54 (1996) 3329.
14 Grinstein B, Savage M J & Wise M B, *Nucl Phys B*, 319 (1989) 271.
15 Choudhury S R, *Phys Rev D*, 56 (1997) 6028.
16 Iltan E O, *Int J Mod Phys A*, 14 (1999) 4365.
17 Choudhury S R & Gaur N, *Phys Rev D*, 66 (2002) 094015.
18 Coleangelo P, Fazio F De, Santorelli P & Scrimieri E, *Phys Rev D*, 53 (1996) 3672.
19 Arhrib A, Chung K, Chiang C W & Yuan T C, *Phys Rev D*, 73 (2006) 075015.
20 Cheung K, Chiang C W, Deshpande N G & Jiang J, *Phys Lett B*, 652 (2007) 285.
21 Chang Q, Li X Q & Yang Y D, *JHEP*, 1002 (2010) 082.
22 Chang Q & Yang Y D, *Nucl Phys B*, 852 (2011) 539.
23 Patrignani C & Particle Data Group, *Chin Phys C*, 40 (2016) 100001.