Probing New Physics through FCNC Transition

Ishtiaq Ahmed[*]
National Centre for Physics, Quaid-i-Azam University Campus, Islamabad 45320, Pakistan

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In this study, we analyze the implications of the non-universal Z' model to the lepton polarization asymmetries and the cp violation for the decay channel $B \to K^*\ell^+\ell^-$ where $\ell = \mu^+\mu^-$. To study the influence of the Z' on the mentioned observables we used the UTFit constraints for the parameters of Z'. We have found that these observables are sensitive to the coupling of the Z' boson with the fermions. Therefore, the accurant measurements of these observables could provide help to extract accurate values of Z' couplings.

1 Introduction

The study of rare B-meson decays which are induced by the flavor changing neutral currents (FCNC) is highly interesting research area in flavor physics because these transitions provide a fertile ground to check the SM and to probe new physics (NP) i.e. the physics beyond the SM. Among the many new physics models, the non universal Z' model looks an attractive extension of the SM (for a detailed review see Ref. [2]). As the behavior of the off diagonal couplings of the non-universal Z' boson with the fermions, the FCNC transitions can occur at tree level as well as this model is help out to resolve the puzzles in the data of rare B-meson decays such as anomaly in the $B_s - \bar{B}_s$ mixing phase [3, 4] and $\pi - K$ puzzle [5], etc.

Further to this, the investigation of non universal family coupling of Z' boson leading to FCNC transitions have also been studied by considering different observables such as branching ratio and forward backward asymmetry [6, 7]. In this context, the behavior of the other observables in the presence of Z' boson may play a crucial role to refine our knowledge about the family of non universal Z' model. With this motivation we have studied single lepton polarization asymmetries, polarized and unpolarized CP violation asymmetries within the SM and in the Z' model. In the context of CP asymmetry, it is important to emphasis here that the FCNC transitions are proportional to three CKM matrix elements, namely, $V_{tb}V_{ts}^*$, $V_{cb}V_{cs}^*$ and $V_{ub}V_{us}^*$ but due to the unitarity condition and neglecting $V_{ub}V_{us}^*$ in comparison of $V_{cb}V_{cs}^*$ and $V_{tb}V_{ts}^*$, the CP asymmetry is highly suppressed in the SM. Therefore, the measurement of CP violation asymmetries in FCNC processes could provide a key evidence for new physics.

The scheme of this report is as follows. The section 2 contains the basic formulation with Z' contribution, the matrix elements and the amplitude for $B \to K^*\ell^+\ell^-$. In section 3, we give the analytical expressions of lepton polarization and cp violation. In sec 4 we present the

2 Theoretical formulation

The Effective Hamiltonian in the SM for the $b \to s\ell^+\ell^-$ transition is as follows

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM} C_i(\mu) Q_i, \tag{1}$$

where G_F is the Fermi coupling constant, Q_i are the four-quark operators, V_{CKM} are the CKM matrix elements and $C_i(\mu)$ are the corresponding Wilson coefficients.

In the presence of Z', the FCNC transitions could occur at tree level and can be described by the following effective Hamiltonian

$$\mathcal{H}^{Z'}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \Big[\Lambda_{sb} C_9^{Z'} Q_9 + \Lambda_{sb} C_{10}^{Z'} Q_{10} \Big] + h.c., \tag{2}$$

where $\Lambda_{sb} = \frac{4\pi e^{-i\phi_{sb}}}{\alpha V^*_{ts} V_{tb}}$, $C_9^{Z'} = \mathcal{R}e(B_{sb}) S_{LL}; C_{10}^{Z'} = \mathcal{R}e(B_{sb}) D_{LL}$ and $S_{LL} = \mathcal{S}^L_{\ell\ell} + \mathcal{S}^R_{\ell\ell}; D_{LL} = \mathcal{S}^L_{\ell\ell} - \mathcal{S}^R_{\ell\ell}$. B_{sb} is the Z' coupling with the b and s quarks and $\mathcal{S}^L_{\ell\ell}, \mathcal{S}^R_{\ell\ell}$ are the left and right handed coupling of Z' with the leptons. The required matrix elements for the channel $B \to K^* \ell^+\ell^-$ are as follows

$$\begin{aligned}
\langle K^*(k,\epsilon)|\bar{s}\gamma^\mu(1\pm\gamma^5)b|B(p)\rangle &= \mp i q_\mu \frac{2m_{K^*}}{s}\epsilon^*\cdot q \Big[A_3(s) - A_0(s)\Big] - \epsilon_{\mu\nu\lambda\sigma} p^\lambda q^\sigma \frac{2V(s)}{(m_B + m_{K^*})} \\
&\pm i\epsilon^*_\mu (m_B + m_{K^*}) A_1(s) \mp i(p+k)_\mu \epsilon^*\cdot q \frac{A_2(s)}{(m_B + m_{K^*})}, \\
\langle K^*(k,\epsilon)|\bar{s} i\sigma_{\mu\nu} q^\nu (1\pm\gamma^5)b|B(p)\rangle &= 2\epsilon_{\mu\nu\lambda\sigma} p^\lambda q^\sigma F_1(s) \pm i\epsilon^*\cdot q \left\{ q_\mu - \frac{(p+k)_\mu}{(m_B^2 - m_{K^*}^2)} \right\} F_3(s) \\
&\pm i\left\{\epsilon^*_\mu (m_B^2 - m_{K^*}^2) - (p+k)_\mu \epsilon^*\cdot q\right\} F_2(s), \\
A_3(s) &= \frac{m_B + m_{K^*}}{2mK^*} A_1(s) - \frac{m_B - m_{K^*}}{2mK^*} A_2(s).
\end{aligned} \tag{3}$$

These seven independent form factors $V(s)$, $A_1(s)$, $A_2(s)$, $A_0(s)$, $F_1(s)$, $F_2(s)$ and $F_3(s)$ are calculated by different non perturbative schemes such as lattice QCD, Quark model (QM) [9] , perturbative QCD (PQCD) and light cone-QCD sum rules (LCSR) [13, 11], etc. By using Eqs. (1)-(3), the total amplitude for the process under consideration can be written in the following way.

$$\begin{aligned}
\mathcal{M}^{tot} = \frac{\alpha G_F}{4\sqrt{2}\pi} V^*_{tb} V_{ts} \Big[&\bar{l}\gamma^\mu(1-\gamma^5) l \times \big(-2\mathcal{A}\epsilon_{\mu\nu\lambda\sigma}\epsilon^* k^\lambda q^\sigma - i\mathcal{B}_1 \epsilon^*_\mu + i\mathcal{B}_2 \epsilon^*\cdot q (p+k)_\mu + \\
&+ i\mathcal{B}_0 \epsilon^*\cdot q q_\mu \big) + \bar{l}\gamma^\mu(1+\gamma^5) l \times \big(-2\mathcal{C}\epsilon_{\mu\nu\lambda\sigma}\epsilon^* k^\lambda q^\sigma - i\mathcal{D}_1 \epsilon^*_\mu + i\mathcal{D}_2 \epsilon^*\cdot q (p+k)_\mu + i\mathcal{D}_0 \epsilon^*\cdot q q_\mu \big) \Big].
\end{aligned} \tag{4}$$

following form.

$$
\begin{aligned}
\mathcal{A} &= 2C_{LL}\mathcal{H}_1 + 4m_bC_7^{eff}\frac{F_1(s)}{s}, \quad \mathcal{B}_1 = 2C_{LL}\mathcal{H}_3 + \frac{4m_b}{s}C_7^{eff}\mathcal{H}_4,\\
\mathcal{B}_2 &= 2C_{LL}\mathcal{H}_6 + 4\frac{m_bC_7^{eff}}{s}\mathcal{H}_5,\\
\mathcal{B}_0 &= \frac{2m_{k^*}}{s}\mathcal{H}_7 - \frac{4m_b}{s}C_7^{eff}F_3(s), \quad \mathcal{C} = \mathcal{A}(C_{LL}\to C_{LR}), \qquad \mathcal{D}_1 = \mathcal{B}_1(C_{LL}\to C_{LR}),\\
\mathcal{D}_2 &= \mathcal{B}_2(C_{LL}\to C_{LR}) \qquad \mathcal{D}_0 = \mathcal{B}_0(C_{LL}\to C_{LR}),\\
\mathcal{H}_1 &= \frac{V(s)}{(mB+m_{K^*})}, \quad \mathcal{H}_3 = (m_B+m_{K^*})A_1(s), \quad \mathcal{H}_4 = (m_B^2-m_{K^*}^2)F_2(s),\\
\mathcal{H}_6 &= \frac{A_2(s)}{(mB+m_{K^*})}, \quad \mathcal{H}_5 = \left[F_2(s) + \frac{s}{(m_B^2-m_{K^*}^2)}F_3(s)\right], \quad \mathcal{H}_7 = (A_3 - A_0),\\
C_{LL} &= C_9^{tot} - C_{10}^{tot}, \quad C_{LR} = C_9^{tot} + C_{10}^{tot}, \quad C_9^{tot} = C_9^{eff} + \Lambda_{sb}C_9^{Z'},\\
C_{10}^{tot} &= C_{10} + \Lambda_{sb}C_{10}^{Z'}. \qquad (5)
\end{aligned}
$$

3 Formulas and analytical analysis of the physical observables

From the total amplitude in E. (4), we can write the decay rate of $B \to K^*\ell^+\ell^-$

$$
\frac{d^2\Gamma(B\to K^*l^+l^-)}{d\cos\theta ds} = \frac{1}{2m_B^3}\frac{2\beta\sqrt{\lambda}}{(8\pi)^3}|\mathcal{M}|^2, \qquad (6)
$$

where $\beta \equiv \sqrt{1-\frac{4m_l^2}{s}}$ and $\lambda \equiv m_B^4 + m_{k^*}^4 + s - 2m_B^2m_{k^*}^2 - 2m_B^2s - 2m_{k^*}^2s$. By using the decay rate, we can find out the single lepton polarization asymmetries and the unpolarized and polarized cp violation asymmetries in $B \to K^*\ell^+\ell^-$ through the follwoing formulae

$$
\begin{aligned}
P_i^{\pm} &= \frac{\frac{d\Gamma(\mathbf{S}^{\pm}=\mathbf{e}_i^{\pm})}{ds} - \frac{d\Gamma(\mathbf{S}^{\pm}=-\mathbf{e}_i^{\pm})}{ds}}{\frac{d\Gamma(\mathbf{S}^{\pm}=\mathbf{e}_i^{\pm})}{ds} + \frac{d\Gamma(\mathbf{S}^{\pm}=-\mathbf{e}_i^{\pm})}{ds}}, \quad \mathcal{A}_{CP}(\mathbf{S}^{\pm}=\mathbf{e}_i^{\pm}) = \frac{\frac{d\Gamma(\mathbf{S}^-)}{ds} - \frac{d\bar{\Gamma}(\mathbf{S}^+)}{ds}}{\frac{d\Gamma}{ds} - \frac{\bar{\Gamma}}{ds}},\\
\mathcal{A}_{CP}(\mathbf{S}^{\pm} &= \mathbf{e}_i^{\pm}) = \frac{1}{2}\left[\frac{\left(\frac{d\Gamma}{ds}\right) - \left(\frac{d\bar{\Gamma}}{ds}\right)}{\left(\frac{d\Gamma}{ds}\right) + \left(\frac{d\bar{\Gamma}}{ds}\right)} \pm \frac{\left(\frac{d\Gamma}{ds}\right)P_i - \{\left(\frac{d\Gamma}{ds}\right)P_i\}_{\Lambda_{sb}\to\Lambda_{sb}^*}}{\left(\frac{d\Gamma}{ds}\right) + \left(\frac{d\bar{\Gamma}}{ds}\right)}\right],\\
\frac{d\Gamma}{ds} &= \frac{d\Gamma(B\to K^*\ell^+\ell^-(\mathbf{S}^-))}{ds}, \quad \frac{d\bar{\Gamma}}{ds} = \frac{d\bar{\Gamma}(B\to K^*\ell^+(\mathbf{S}^+))\ell^-}{ds}, \qquad (7)
\end{aligned}
$$

where i denotes the longitudinal (L),normal (N) and transverse (T) and $\mathbf{S}^{\pm}$ is the spin direction of $l^{\pm}$. The relation between the polarized and unpolarized invariant dilepton mass spectrum for the $B \to K^*l^+l^-$ read as

Table 1: Numerical values of $\langle P_L \rangle$ in Z' model for scenario-I

		$\langle P_L \rangle$ at $D_{LL} = 0$				$\langle P_L \rangle$ at $S_{LL} = 0$			
ϕ_{sb} in Degree	Decay Channel	S_{LL} -6.7		S_{LL} 1.1		D_{LL} -9.3		D_{LL} -4.1	
		$B_{sb} = 0.87$	1.31	0.87	1.31	0.87	1.31	0.87	1.31
-65°	$B \to K^* \mu^+ \mu^-$	-0.785	-0.715	-0.774	-0.757	-0.597	-0.485	-0.731	-0.679
	$B \to K^* \tau^+ \tau^-$	-0.423	-0.347	-0.526	-0.519	-0.515	-0.476	-0.538	-0.532
-79°	$B \to K^* \mu^+ \mu^-$	-0.741	-0.651	-0.782	-0.772	-0.573	-0.442	-0.728	-0.669
	$B \to K^* \tau^+ \tau^-$	-0.443	-0.354	-0.517	-0.506	-0.454	-0.394	-0.509	-0.490

For the numerical analysis, we used the values of different input parameters and Wilson coefficients from [12, 13] while for Z' parameters we used the UTFit collaboration results [14].

To see the NP, we have plotted single lepton polarization asymmetries as a function of the momentum square s. (see Figs. 1-5 of ref. [1]). From these figures one can extract that the longitudinal and normal polarization asymmetries are sensitive to the Z' parameters at low s region for the case of muons while the transverse asymmetry is tiny, both, in the SM and in the Z' model. Some numerical values of the P_L are listed in Table 1 by using $\mathcal{S}_1$ scenario of Z' model (see ref. [1] for details).

To see the variation in the average values of single lepton polarization asymmetries $\langle P_i \rangle$, where $i = L, N$ or T, due to the influence of Z' boson effect see Figs. (6)-(11) of ref. [1] where we have plotted these asymmetries against the different coupling parameters of Z' models. From these graphs we have found that $\langle P_L \rangle$ sensitive to S_{LL} i.e. the NP contribution coming from Wilson coefficient C_9 while the values of $\langle P_N \rangle$ significantly effected by D_{LL} i.e. the NP contribution coming from Wilson coefficient C_{10}. Moreover, $\langle P_N \rangle$ value is influenced by the new weak phase ϕ_{sb} when tauons are the final state leptons.

Now we turn our attention to analysis of another interesting observable i.e. CP violation. As we have mentioned earlier in the introduction that for $b \to s\ell^+\ell^-$ transition the value of CP violation is negligible and any measurement of this observable is a clear sign of new physics. However, we have found that both the polarized and unpolarized CP violation asymmetries for $B \to K^* \mu^+ \mu^-$ are suppressed in the SM and in the Z' model. Similarly, CP violation when one of the final state tauon is transversely polarized is also found to be suppressed and therefore, we do not include these asymmetries in our numerical discussion. The other CP asymmetries $\mathcal{A}_{CP}$ and $\mathcal{A}^i_{CP}$ (where $i = L, N$) for $B \to K^* \tau^+ \tau^-$ are displayed in Figs. (12)-(15).From these figures, we have found that the values of direct unpolarized CP violation asymmetry $\mathcal{A}_{CP}$ is not significantly changed when we change the values of new weak phase ϕ_{sb} and D_{LL} but strongly depend on the value of S_{LL}. In contrast to the $\mathcal{A}_{CP}$ it is found that the $\mathcal{A}^L_{CP}$ is almost insensitive to the value of S_{LL} but sensitive to the values of D_{LL} . However, $\mathcal{A}^N_{CP}$ is sensitive for both S_{LL} and D_{LL}.

4 Conclusion

As the CP violation asymmetries are negligible in the SM and in this analysis it is found that $\mathcal{A}_{CP}$, $\mathcal{A}_{CP}^{L}$ and $\mathcal{A}_{CP}^{N}$ are considerably enhanced in the presence of Z' when tauons are the final state leptons. Similarly, the lepton polarization asymmetries are also significantly change their values from the SM values when we incorporate the effects of Z'. Therefore, the accurate measurements of these observables could be depict the precise values of the new weak phase ϕ_{sb} and coupling of Z' boson with the leptons and quarks.

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