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Effect of Z'-mediated flavor-changing neutral currents on $B\rightarrow\pi K$ decay

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The effect of a Z'-mediated flavor-changing neutral current (FCNC) on the $B\rightarrow\pi K$ decay process has been studied. We find the branching ratio is enhanced from its standard model (SM) value and gives the possibility of new physics.

Keywords: Bottom mesons, Z' boson, Decays of bottom mesons, π and K mesons

1 Introduction

In recent years, the decays of B-mesons into πK final states have been a very active area of research both experimentally and theoretically[1-26] because these decays can be used to search physics beyond the SM. There are four different decay channels[19] (and their anti-particle decay channels) for $B\rightarrow\pi K$ processes, depending on the electric charge configuration. All the $B\rightarrow\pi K$ modes have already been observed in experiment and their CP-averaged branching ratios have been measured by BaBar and Belle Collaborations[20-26]. The direct CP asymmetry for the $B\rightarrow\pi K$ modes have been measured but results have no decisive conclusions until recently[20,27-32]. There are three kinds of models[33] used for theoretical calculations of the branching ratios and CP asymmetries (A_{CP}) for non-leptonic charmless B decay modes: the conventional factorization (CF) model[34-37], the QCD-improved factorization (QCDF) model[38-40] and the perturbative QCD (PQCD) model[41-47]. The main problem is to calculate the strong phase and hence, the CP asymmetry theoretically. In CF model the strong phases are calculated from the imaginary parts of the respective Wilson coefficients. QCDF predicts a small strong phase difference between the dominant amplitudes. In PQCD predictions, annihilation and exchange topologies are given more weightage than in QCDF. They can generate a sizable strong phase. $B\rightarrow\pi K$ and related decays are also studied in the heavy quark limit of QCD using the soft collinear effective theory[48,49] (SCET). The B decays[50-52] induced by the flavor-changing neutral current (FCNC) transitions are very important to probe the quark-flavor sector of the SM. In the SM, they arise from one-loop diagrams and are generally suppressed in comparison to the tree diagrams. Nevertheless, one-loop FCNC processes can be enhanced by orders of magnitude in some cases due to the presence of new physics. New physics comes into play in B decays in two different ways: (a) through a new contribution to the Wilson coefficients, and (b) through a new structure in the effective Hamiltonian, which are both absent in the SM. In this paper, we study $B\rightarrow\pi K$ decay considering the effect of Z'-mediated FCNC which modifies the Wilson coefficients and changes the effective Hamiltonian, and gives a new result for the branching ratio.

In the Z' sector, there has been a great deal of investigation to understand the underlying physics beyond the SM[53-72]. It has been shown that a leptophobic Z' boson can appear in E_6 gauge models due to mixing of gauge kinetic terms[73-77]. Flavor mixing can be induced at the tree level in the up-type and/or down-type quark sector after diagonalizing their mass matrices. 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 flavor-changing neutral currents[73,74,78-84] (FCNCs) among the ordinary down quark types. Tree level FCNC interactions can also be induced by an additional Z' boson on the up-type quark sector[85]. With FCNCs, the Z' boson contributes at tree level, and its contribution will interfere with the SM contributions. The flavor-changing couplings will give new contributions to the SM operators and give new results.

2 $B\to\pi K$ Decay in the Standard Model

Let us consider the $B\to\pi K$ decay process. In the standard model, this decay involves $\bar{b}\to\bar{s}q\bar{q}$ transitions through exchange of W-boson. The effective Hamiltonian[86-93] for ΔB=1, describing the decay process $B\to\pi K$ can be written as:

$$H_{eff}^{SM}=\frac{G_F}{\sqrt{2}}\sum_{q=u,c}\lambda_q\left[C_1Q_1^q+C_2Q_2^q+\sum_{i=3}^{10}C_iQ_i+C_gQ_g\right]+h.c.,\quad\ldots(1)$$

where $\lambda_q=V_{qb}^{*}V_{qs}$, C_i's are Wilson coefficients and Q_i's are local operators containing quark and gluon fields[86]. The current-current operators induced by W-boson exchange are given by:

$$Q_1^q=\left(\bar{b}_\alpha q_\beta\right)_{V-A}\left(\bar{q}_\beta s_\alpha\right)_{V-A},\qquad Q_2^q=\left(\bar{b}_\alpha q_\alpha\right)_{V-A}\left(\bar{q}_\beta s_\beta\right)_{V-A}.\quad\ldots(2)$$

The Q_i's, $i=3,4,5,6$ i.e.

$$Q_3=\left(\bar{b}_\alpha s_\alpha\right)_{V-A}\sum_q\left(\bar{q}_\beta q_\beta\right)_{V-A},$$
$$Q_4=\left(\bar{b}_\alpha s_\beta\right)_{V-A}\sum_q\left(\bar{q}_\beta q_\alpha\right)_{V-A},$$
$$Q_5=\left(\bar{b}_\alpha s_\alpha\right)_{V-A}\sum_q\left(\bar{q}_\beta q_\beta\right)_{V+A},$$
$$Q_6=\left(\bar{b}_\alpha s_\beta\right)_{V-A}\sum_q\left(\bar{q}_\beta q_\alpha\right)_{V+A},\quad\ldots(3)$$

are the QCD penguin operators, summed over the quark flavors $q=u,d,s,c,b$ and the other Q_i's, i=7,8,9,10 i.e.

$$Q_7=\frac{3}{2}\left(\bar{b}_\alpha s_\alpha\right)_{V-A}\sum_q e_q\left(\bar{q}_\beta q_\beta\right)_{V+A},$$
$$Q_8=\frac{3}{2}\left(\bar{b}_\alpha s_\beta\right)_{V-A}\sum_q e_q\left(\bar{q}_\beta q_\alpha\right)_{V+A},$$
$$Q_9=\frac{3}{2}\left(\bar{b}_\alpha s_\alpha\right)_{V-A}\sum_q e_q\left(\bar{q}_\beta q_\beta\right)_{V-A},$$
$$Q_{10}=\frac{3}{2}\left(\bar{b}_\alpha s_\beta\right)_{V-A}\sum_q e_q\left(\bar{q}_\beta q_\alpha\right)_{V-A},\quad\ldots(4)$$

are the electroweak penguin operators, where e_q is the charge of the quark , and lastly

$$Q_g=\frac{g_s}{8\pi^2}m_b\bar{b}\sigma^{\mu\nu}\left(1-\gamma_5\right)G_{\mu\nu}s,\quad\ldots(5)$$

is the chromomagnetic dipole operator. Here, $\left(\bar{q}_1q_2\right)_{V\pm A}=\bar{q}_1\gamma^\mu\left(1\pm\gamma_5\right)q_2$.

Using QCD factorization[94] rule, we can write the decay amplitude of $B\to\pi K$ as:

$$A\left(B^-\to\pi^-\bar{K}^0\right)=\sum_{q=u,c}\lambda_q A_{\pi\bar{K}}\left[\delta_{qu}\beta_2+\alpha_4^q-\frac{1}{2}\alpha_{4,EW}^q+\beta_3^q+\beta_{3,EW}^q\right]\quad\ldots(6)$$

$$\sqrt{2}A\left(B^-\to\pi^0K^-\right)=\sum_{q=u,c}\lambda_q A_{\pi\bar{K}}\left[\delta_{qu}(\alpha_1+\beta_2)+\alpha_4^q+\alpha_{4,EW}^q+\beta_3^q+\beta_{3,EW}^q\right]+\sum_{q=u,c}\lambda_q A_{\bar{K}\pi}\left[\delta_{qu}\alpha_2+\frac{3}{2}\alpha_{3,EW}^q\right]\quad\ldots(7)$$

$$A\left(\bar{B}^0\to\pi^+K^-\right)=\sum_{q=u,c}\lambda_q A_{\pi\bar{K}}\left[\delta_{qu}\alpha_1+\alpha_4^q+\alpha_{4,EW}^q+\beta_3^q-\frac{1}{2}\beta_{3,EW}^q\right]\quad\ldots(8)$$

$$\sqrt{2}A\left(\bar{B}^0\to\pi^0\bar{K}^0\right)=\sum_{q=u,c}\lambda_q A_{\pi\bar{K}}\left[-\alpha_4^q+\frac{1}{2}\alpha_{4,EW}^q-\beta_3^q+\frac{1}{2}\beta_{3,EW}^q\right]+\sum_{q=u,c}\lambda_q A_{\bar{K}\pi}\left[\delta_{qu}\alpha_2+\frac{3}{2}\alpha_{3,EW}^q\right].\quad\ldots(9)$$

where $\alpha_i^q(\pi K)$ and $\beta_i^q(\pi K)$ are the coefficients of the flavor operators[92,94]. The parameters $A_{\pi\bar{K}}\left(A_{\bar{K}\pi}\right) = i\frac{G_F}{\sqrt{2}}m_B^2 F_0^{B\to\pi(K)} f_{K(\pi)}$. The standard model contributions to Wilson coefficients, which are relevant for $B\to\pi K$ decay , are given by[92]

$$\begin{aligned}
&C_1^{SM} \cong 1.077, C_2^{SM} \cong -0.175, C_3^{SM} \cong 0.012,\\
&C_4^{SM} \cong -0.33, C_5^{SM} \cong 0.0095, C_6^{SM} \cong -0.039\\
&C_7^{SM} \cong 0.0001, C_8^{SM} \cong 0.0004, C_9^{SM} \cong -0.01,\\
&C_{10}^{SM} \cong 0.0019, C_g^{SM} \cong -0.149
\end{aligned} \quad \ldots (10)$$

From Eq. (10), it is clear that within the SM, $B\to\pi K$ decay process is dominated by the QCD penguin operator Q_4. Isospin violating contributions to the decay amplitudes arise from the current-current operators Q_1^u and Q_2^u. There may be a possibility of large electroweak penguin contributions[13-18] in $B\to\pi K$, but since the Wilson coefficients $C_{7\text{-}10}$ are very small, the electroweak penguin contributions are suppressed in the SM.

The branching ratio corresponding to the decay amplitude can be written as:

$$B(B\to\pi K)\,|_{SM} = \frac{1}{8\pi}\frac{|P|}{m_B^2}\left|A(B\to\pi K)\right|^2\frac{1}{\Gamma_{tot}}, \quad \ldots (11)$$

where

$$|P| = \frac{\left[\left(m_B^2-(m_K+m_\pi)^2\right)\left(m_B^2-(m_K-m_\pi)^2\right)\right]^{\frac{1}{2}}}{2m_B}. \quad \ldots (12)$$

The SM predictions for the branching ratios of the four decay modes of $B\to\pi K$ are given[92] as :

$$\begin{aligned}
&B\left(B^-\to\pi^-\bar{K}^0\right) = 31.06\times10^{-6},\\
&B\left(B^-\to\pi^0 K^-\right) = 17.31\times10^{-6},\\
&B\left(\bar{B}^0\to\pi^+ K^-\right) = 25.87\times10^{-6},\\
&B\left(\bar{B}^0\to\pi^0\bar{K}^0\right) = 11.41\times10^{-6}.
\end{aligned} \quad \ldots (13)$$

The recent experimental results for the four branching ratios of $B\to\pi K$ decay are given[95-99] in units of 10^{-6} as:

Mode	BARBAR[95,97,98]	BELLE[99]	Average[96]
$B\left(B^-\to\pi^-\bar{K}^0\right)$	23.9±1.1±1.0	$22.9^{+0.8}_{-0.7}\pm1.3$	23.40±1.06
$B\left(B^-\to\pi^0 K^-\right)$	13.3±0.56±0.6	$12.4\pm0.5^{+0.7}_{-0.6}$	12.83±0.59
$B\left(\bar{B}^0\to\pi^+ K^-\right)$	19.7±0.6±0.6	$20.0\pm0.4^{+0.9}_{-0.8}$	19.83±0.63
$B\left(\bar{B}^0\to\pi^0\bar{K}^0\right)$	10.5±0.7±0.5	$9.2^{+0.7+0.6}_{-0.6-0.7}$	9.89±0.63

… (14)

The ratios R_c, R_n and R of $B\to\pi K$ decay are defined as:

$$\begin{aligned}
R_c &= 2\left[\frac{B\left(B^+\to\pi^0K^+\right)+B\left(B^-\to\pi^0K^-\right)}{B\left(B^+\to\pi^+K^0\right)+B\left(B^-\to\pi^-\bar{K}^0\right)}\right],\\
R_n &= \frac{1}{2}\left[\frac{B\left(B^0\to\pi^-K^+\right)+B\left(\bar{B}^0\to\pi^+K^-\right)}{B\left(B^0\to\pi^0K^0\right)+B\left(\bar{B}^0\to\pi^0\bar{K}^0\right)}\right],\\
R &= \left[\frac{B\left(B^0\to\pi^-K^+\right)+B\left(\bar{B}^0\to\pi^+K^-\right)}{B\left(B^+\to\pi^+K^0\right)+B\left(B^-\to\pi^-\bar{K}^0\right)}\right]\frac{\tau_{B^+}}{\tau_{B^0}}.
\end{aligned} \quad \ldots (15)$$

In the SM, the values of R_c, R_n and R are: R_c = 1.11, R_n = 1.13 and R = 0.83 … (16)

According to the recent experimental results the values of R_c, R_n and R are:

$R_c = 1.00 \pm 0.08$, $R_n = 0.79 \pm 0.08$ and $R = 0.82 \pm 0.06$ … (17)

From Eqs (16) and (17), it is clear that the R_c and R_n are approximately equal in the SM, but their experimental values are different from the SM prediction. Whereas the experimental value of R is consistent with the SM value. From Eqs (13) and (14), it is clear that there are inconsistencies between the branching ratio values of experimental results with the SM. Similarly, inconsistencies also exist in the CP asymmetries of $B\to\pi K$ decay[1–19]. These inconsistencies between the CP asymmetries and the R_c - R_n measurements and the SM results are known as

$B\rightarrow\pi K$ puzzles. Within the SM, the πK puzzles cannot be resolved. The supersymmetric extension[92] of the SM is an interesting candidate for explaining the πK puzzles.

3 Effect of Z' Boson in $B\rightarrow\pi K$ Decay

With FCNCs, the Z' boson contributes at tree level, and its contribution will interfere with the SM contributions. The effective Hamiltonian of $\bar{b}\rightarrow\bar{s}q\bar{q}$ transition mediated by the Z' boson[100,101] is:

$$H_{eff}^{Z'}=\frac{G_F}{\sqrt{2}}\left(\frac{g' M_Z}{g_Y M_{Z'}}\right)^2\sum_{q=u,c}\lambda_q \left[C_1Q_1^q+C_2Q_2^q+\sum_{i=3}^{10}C_iQ_i+C_gQ_g\right]+h.c. \quad \ldots (18)$$

where $g_Y=e/(\sin\theta_W\cos\theta_W)$ and g' is the gauge coupling associated with the $U(1)'$ group. The Z' boson contributes to the QCD penguin operators $Q_{3(5)}$ as well as EW penguin operators $Q_{7(9)}$[1-6,101]. The resulting Z' contributions to the Wilson coefficients corresponding to QCD penguin operators at the weak scale $\Delta_{3(5)}\approx 0$. But the flavor-changing couplings of the Z' with the left-handed fermions will contribute to the Q_9 and Q_7 operators for left (right)-handed couplings at the flavor-conserving vertex i.e. Q_9 and Q_7 operators receive new contributions from Z' boson. Similarly, right-handed flavor-changing couplings also yield new contributions. In other words, we can say Wilson coefficients of the corresponding operators are modified due to Z' effect and hence Hamitonian changes. The net effective Hamiltonian for $B\rightarrow\pi K$ decay can be written as:

$$H_{eff}^{SM+Z'}=\frac{G_F}{\sqrt{2}}\sum_{q=u,c}\lambda_q\left[C_1Q_1^q+C_2Q_2^q+\sum_{i=3}^{10}C_iQ_i+C_gQ_g\right]\left[1+\left(\frac{g' M_Z}{g_Y M_{Z'}}\right)^2\right]+h.c. \quad \ldots (19)$$

and the corresponding branching ratio is given as:

$$B(B\rightarrow\pi K)\,|_{SM+Z'}=\frac{1}{8\pi}\frac{|P|}{m_B^2}\left|A(B\rightarrow\pi K)\right|^2\frac{1}{\Gamma_{tot}}\left[1+\left(\frac{g' M_Z}{g_Y M_{Z'}}\right)^2\right]^2 \quad \ldots (20)$$

In the next section, we use this formula for the calculation of branching ratio for $B\rightarrow\pi K$ decay in the presence of Z' boson.

4 Results and Discussion

In this section, we calculate the branching ratio for $B\rightarrow\pi K$ decay in the presence of Z' boson using all the recent data[102]: $m_{\pi^\pm}=139.570\ MeV$, $m_{\pi^0}=134.976\,MeV$, $m_{K^\pm}=493.677\ MeV$, $m_{K^0}=497.648\,MeV$, $m_{B^\pm}=(5279.0\pm0.5)\,MeV$, $m_{B^0}=(5279.4\pm0.5)\ MeV$, mean lifetime $\tau_{B^\pm}=(1.671\pm0.018)\times10^{-12}\,s$, $\tau_{B^0}=(1.536\pm0.014)\times10^{-12}\,s$, M_Z = 91.1876 GeV, Fermi constant $G_F=1.16639\times10^{-5}\,GeV^{-2}$, decay constants f_B=190 MeV, f_K=160 MeV, f_π=130 MeV and $\sin^2\theta_W=0.23$. We have taken g'/g_Y = 10. In a study of B meson decays with Z'-mediated flavor-changing neutral currents[100], a model-dependent lower bound on the mass of Z' boson around 500 GeV and an upper bound around 1 TeV was obtained. Our investigations in both the left-right symmetric model[103] and potential model[104] give a lower bound of $M_{Z'}\ \geq\ 500\,GeV$ and an upper bound of 1 TeV. There are thus good motivations for an extra Z' boson, with a mass range[105] 500 GeV –1 TeV.

Using the lower limit mass of Z' boson, $M_{Z'}$ = 500 GeV and all recent data in Eq. (20), we get :

$$\begin{aligned}
B(B^-\rightarrow\pi^-\bar{K}^0)\,|_{SM+Z'} &= 58.12\times10^{-5},\\
B(B^-\rightarrow\pi^0K^-)\,|_{SM+Z'} &= 32.39\times10^{-5},\\
B(\bar{B}^0\rightarrow\pi^+K^-)\,|_{SM+Z'} &= 48.41\times10^{-5},\\
B(\bar{B}^0\rightarrow\pi^0\bar{K}^0)\,|_{SM+Z'} &= 21.35\times10^{-5}.
\end{aligned} \quad \ldots (21)$$

Again using the upper limit mass of Z' boson, $M_{Z'}$ = 1000 GeV and all recent data in Eq. (20), we get:

$$B\left(B^{-}\to\pi^{-}\bar{K}^{0}\right)\big|_{SM+Z'} = 10.41\times10^{-5},$$
$$B\left(B^{-}\to\pi^{0}K^{-}\right)\big|_{SM+Z'} = 5.81\times10^{-5},$$
$$B\left(\bar{B}^{0}\to\pi^{+}K^{-}\right)\big|_{SM+Z'} = 8.67\times10^{-5},$$
$$B\left(\bar{B}^{0}\to\pi^{0}\bar{K}^{0}\right)\big|_{SM+Z'} = 3.82\times10^{-5}. \quad \dots (22)$$

From Eqs (21) and (22), it is clear that depending on the precise value of $M_{Z'}$, the Z'-mediated FCNCs gives sizable contributions to $B\to\pi K$ decay process. The branching ratio for $B\to\pi K$ decay process is enhanced from its standard model value [Eq. (13)]. This is due to the effect of Z'-mediated flavor-changing neutral currents at the tree level. Similarly the CP asymmetry in $B\to\pi K$ decay process is also affected due to Z'-mediated flavor-changing neutral currents. Hence, there may be the possibility of new physics effects in the $B\to\pi K$ decay process. We hope the effect of Z' boson in the $B\to\pi K$ decay process may provide a solution for $B\to\pi K$ puzzles. These facts lead to enrichment in the phenomenology of both the Z'-mediated FCNCs and $B\to\pi K$ decay process.

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