Constraints on the Phase γ and New Physics from $B \to K\pi$ Decays

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Recent results from CLEO on $B \to K\pi$ indicate that the phase γ may be substantially different from that obtained from other fit to the KM matrix elements in the standard model. We show that γ extracted using $B \to K\pi, \pi\pi$ is sensitive to new physics occurring at loop level. It provides a powerful method to probe new physics in electroweak penguin interactions. Using effects due to anomalous gauge couplings as an example, we show that within the allowed ranges for these couplings information about γ obtained from $B \to K\pi, \pi\pi$ can be very different from the standard model prediction.

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The CLEO Collaboration has recently measured the four $B \to K\pi$ branching ratios with [1], $\mathcal{B}(B^\pm \to \pi^\pm K^0) = (1.82^{+0.46}_{-0.4} \pm 0.16) \times 10^{-5}$, $\mathcal{B}(B^\pm \to K^\pm\pi^0) = (1.21^{+0.30+0.21}_{-0.28-0.14}) \times 10^{-5}$, $\mathcal{B}(B \to K^\pm\pi^\mp) = (1.88^{+0.28}_{-0.26} \pm 0.13) \times 10^{-5}$, and $\mathcal{B}(B \to K^0\pi^0) = (1.48^{+0.59+0.24}_{-0.51-0.33}) \times 10^{-5}$. It is suppressing that these branching ratios turn out to be close to each other because naive expectation of strong penguin dominance would give $R = \mathcal{B}(K^\pm\pi^0)/\mathcal{B}(K\pi^\pm) \sim 1/2$ and model calculations for $\mathcal{B}(B^0 \to K^0\pi^0)$ would obtain a much smaller value. The closeness of the branching ratios with charged mesons in the final states may be an indication of large interference effects of tree, strong, and electroweak penguin interactions [2]. It has been shown that using information from these decays and $B^\pm \to \pi^\pm\pi^0$ decays, the phase angle γ of the Kobayashi-Maskawa (KM) matrix can be constrained [3] and determined [4] in the standard model (SM). Using the present central values for these branching ratios we find that the constraint obtained on γ may have a potential problem with $\gamma = (59.5^{+8.5}_{-7.5})^\circ$ obtained from other constraints [5].

If there is new physics beyond the SM the situation becomes complicated [6,7]. It is not possible to isolate different new physics sources in the most general case. However, one can extract important information for the class of models where significant new physics effects show up only at loop levels for B decays [6,7]. In this paper we study how new physics of the type described above can affect the results using anomalous three gauge boson couplings as an example for illustration.

New physics due to anomalous three gauge boson couplings is a perfect example of models where new physics effects appear only at loop level in B decays. Effects due to anomalous couplings do not appear at tree level for B decays to the lowest order, and they do not affect CP violation and mixings in $K^0 - \bar{K}^0$ and $B - \bar{B}$ systems at one loop level. Therefore they do not affect the fitting to the KM parameters obtained in Ref. [5]. However, they affect the constraint on and determination of γ using experimental results from $B \to K\pi, \pi\pi$, and affect the B decay branching ratios.

The effective Hamiltonian $H_{\rm eff} = (G_F/\sqrt{2}) \times [V_{ub}^* V_{uq}(c_1 O_1 + c_2 O_2) - V_{tb}^* V_{tq} \sum_{i=3-10} c_i O_i]$ responsible for B decays has been studied by many authors [8]. We will use the values of c_i obtained for the SM in Ref. [9] with

$$\begin{aligned}
&c_1 = -0.313, \quad c_2 = 1.150, \quad c_3 = 0.017, \\
&c_4 = -0.037, \quad c_5 = 0.010, \quad c_6 = -0.046, \\
&c_7 = -0.001\alpha_{em}, \quad c_8 = 0.049\alpha_{em}, \\
&c_9 = -1.321\alpha_{em}, \quad c_{10} = 0.267\alpha_{em}.
\end{aligned} \tag{1}$$

The Wilson coefficients are modified when anomalous couplings are included. They will generate nonzero c_{3-10} [10]. Their effects on $B \to K\pi$ mainly come from c_{7-10}. To the leading order in QCD corrections, the new contributions to c_{7-10}^{AC} due to various anomalous couplings are given by

$$\begin{aligned}
c_7^{AC}/\alpha_{em} &= -0.287\Delta\kappa^\gamma - 0.045\lambda^\gamma \\
&\quad + 1.397\Delta g_1^Z - 0.145 g_5^Z, \\
c_8^{AC}/\alpha_{em} &= -0.082\Delta\kappa^\gamma - 0.013\lambda^\gamma \\
&\quad + 0.391\Delta g_1^Z - 0.041 g_5^Z, \\
c_9^{AC}/\alpha_{em} &= -0.337\Delta\kappa^\gamma - 0.053\lambda^\gamma \\
&\quad - 5.651\Delta g_1^Z + 0.586 g_5^Z, \\
c_{10}^{AC}/\alpha_{em} &= 0.069\Delta\kappa^\gamma + 0.011\lambda^\gamma \\
&\quad + 1.143\Delta g_1^Z - 0.119 g_5^Z.
\end{aligned} \tag{2}$$

In the above we have used a cutoff $\Lambda = 1$ TeV for terms proportional to $\Delta\kappa^\gamma$ and Δg_1^Z. Contributions from other anomalous couplings are suppressed by additional factors of order $(m_b^2, m_B^2)/m_W^2$ which can be safely neglected. There are constraints on the anomalous gauge couplings [11,12]. LEP experiments obtain [12], $-0.217 < \Delta\kappa^\gamma < 0.223$, $-0.158 < \lambda^\gamma < 0.074$, and $-0.113 < \Delta g_1^Z < 0.126$ at the 95% C.L. Assuming that g_5^Z is the same order as Δg_1^Z, it is clear that the largest possible contribution may come from Δg_1^Z. In our later discussions we consider Δg_1^Z effects only.

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To see possible deviations from the SM predictions for $B \to K\pi$ data, we carried out a calculation using factorization following Ref. [13], with $V_{us} = 0.2196$, $V_{cb} \approx -V_{ts} = 0.0395$, and $|V_{ub}| = 0.08 V_{cb}$ [14]. The branching ratios as functions of γ are shown in Fig. 1. In this figure we used $m_s = 100$ MeV which is at the middle of the range from lattice calculations [15] and the number of colors $N_c = 3$. Since penguin dominates the branching ratio for $\mathcal{B}(B^+ \to K^0\pi^+)$ which is insensitive to γ, we normalize the branching ratios to $\mathcal{B}(B^+ \to K^0\pi^+)$ to reduce possible uncertainties in the overall normalization of form factors involved.

From Fig. 1, we see that the central values for the branching ratios for the ones with at least one charged meson in the final states require the angle γ to be within 75° to 80° rather than the best fit value $\gamma_{\text{best}} = 59.5°$ in Ref. [5]. Larger γ is also indicated by other rare B decay data [16]. When effects due to Δg_1^Z are included the situation can be relaxed. The effects of Δg_1^Z on $B^+ \to K^0\pi^+, K^+\pi^-$ are very small, but are significant for $B^+ \to K^+\pi^0$ and $B \to K^0\pi^0$. With positive Δg_1^Z in its allowed range, it is possible for the relative ratios of $\mathcal{B}(B^+ \to K^+\pi^0)$ to the other charged modes to be in agreement with data for $\gamma = \gamma_{\text{best}}$. We note that Δg_1^Z does not affect the ratio $\mathcal{B}(B^0 \to K^+\pi^-)/\mathcal{B}(B^+ \to K^0\pi^+)$. Its experimental value prefers γ to be close to 75°. Of course, we also note that this situation can be improved by treating N_c as a free parameter to take into account certain nonfactorizable effects. We find that with $N_c \approx 1.35$, the central experimental values for the branching ratios of B decays into charged mesons in the final states can be reproduced for $\gamma = \gamma_{\text{best}}$. It is not possible to bring $\mathcal{B}(B^0 \to K^0\pi^0)$ up to the experimental central value even with allowed Δg_1^Z and reasonable values for N_c and m_s.

If the present experimental central values will persist and factorization approximation with $N_c = 3$ is valid, new physics may be needed. Needless to say that we have to wait for more accurate data to draw firmer conclusions. Also due to our inability to reliably calculate the hadronic matrix elements, one should be careful in drawing conclusions with factorization calculations. However, we would like to point out that data on rare B to $K\pi$ decays may provide a window to look for new physics beyond the SM. Of course, to have a better understanding of the situation one needs to find methods which are able to extract γ in a model independent way and in the presence of new physics. In the following we will analyze some rare B to $K\pi$ decay data in a more model independent way.

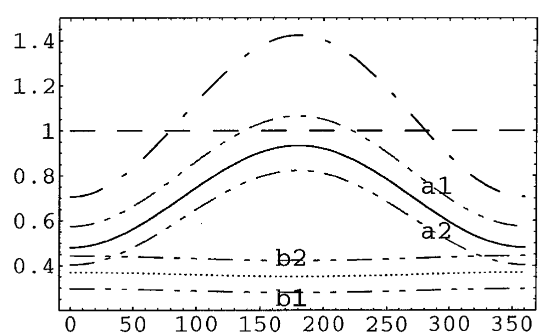

FIG. 1. CP-averaged branching ratios normalized to $\mathcal{B}(B^+ \to K^0\pi^+)$ vs γ for $B^+ \to K^0\pi^+$ (dashed line), $B^+ \to K^+\pi^0$ (solid line), $B^0 \to K^+\pi^-$ (dot-dashed line), and $B^0 \to K^0\pi^0$ (dotted line) for the SM with $m_s = 100$ MeV. The curves a_1, b_1 and a_2, b_2 are for Δg_1^Z equal to -0.113 and 0.126, respectively.

Model independent constraint on γ can be obtained using branching ratios for $B^\pm \to K\pi$ and $B^\pm \to \pi\pi$ from symmetry considerations. This method would only need information from charged B decays to $K\pi$ and $\pi\pi$, and therefore this method is not affected by the uncertainties associated with neutral B decays to $K\pi$ modes. Using the SU(3) relation and factorization estimate for the SU(3) breaking effect among $B^\pm \to K\pi$ and $B^\pm \to \pi\pi$, one obtains [3,4]

$$\begin{aligned} A(\pi^+K^0) + \sqrt{2}A(\pi^0K^+) &= \epsilon A(\pi^+K^0) \\ &\quad \times e^{i\Delta\phi}\,\frac{e^{i\gamma} - \delta_{EW}}{1 - \delta'_{EW}}\,, \\ \delta_{EW} &= -\frac{3}{2}\,\frac{|V_{cb}||V_{cs}|}{|V_{ub}||V_{us}|}\,\frac{c_9 + c_{10}}{c_1 + c_2}\,, \\ \delta'_{EW} &= \frac{3}{2}\,\frac{|V_{tb}||V_{td}|}{|V_{ub}||V_{ud}|}\,e^{i\alpha}\,\frac{c_9 + c_{10}}{c_1 + c_2}\,, \\ \epsilon &= \sqrt{2}\,\frac{|V_{us}|}{|V_{ud}|}\,\frac{f_K}{f_\pi}\,\frac{|A(\pi^+\pi^0)|}{|A(\pi^+K^0)|}\,, \end{aligned} \tag{3}$$

where $\Delta\phi$ is the difference of the final state elastic re-scattering phases $\phi_{3/2,1/2}$ for $I = 3/2, 1/2$ amplitudes. For $f_K/f_\pi = 1.22$ and $\mathcal{B}(B^\pm \to \pi^\pm\pi^0) = (0.54^{+0.21}_{-0.20} \pm 0.15) \times 10^{-5}$, we obtain $\epsilon = 0.21 \pm 0.06$.

The parameter δ'_{EW} is of the order of $c_{9,10}/c_{1,2}$, which is much smaller than one and will be neglected in our later discussions. δ_{EW} is a true measure of electroweak penguin interactions in hadronic B decays and provides an easier probe of these interactions compared with other methods [17]. In the above, contributions from $c_{7,8}$ have been neglected, which is safe in the SM because they are small. With anomalous couplings this is still a good approximation. In general, the contributions from $c_{7,8}$ may be substantial. In that case the expression becomes more complicated. But one can always absorb the contribution into an effective δ_{EW}. In the SM for $r_v = |V_{ub}|/|V_{cb}| = 0.08$ and $|V_{us}| = 0.2196$ [14], $\delta_{EW} = 0.81$. Smaller r_v implies larger δ_{EW}. Had we used $r_v = 0.1$, δ_{EW} would be 0.65 as in Ref. [3,4]. With anomalous couplings, we find

$$\begin{aligned} \delta_{EW} = 0.81(1 &+ 0.26\Delta\kappa^\gamma + 0.04\lambda^\gamma \\ &+ 4.33\Delta g_1^Z - 0.45 g_5^Z)\,. \end{aligned} \tag{4}$$

The value for δ_{EW} can be different from the SM prediction. It is most sensitive to Δg_1^Z. Within the allowed range of $-0.113 < \Delta g_1^Z < 0.126$ [12], δ_{EW} can vary in the range $\sim 0.40 - 1.25$.

Neglecting the small tree contribution to $B^+ \to \pi^+ K^0$, one obtains

$$\cos\gamma = \delta_{EW} - \frac{(r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2)}{2\epsilon(\cos\Delta\phi + \epsilon\delta_{EW})}, \tag{5}$$

$$r_+^2 - r_-^2 = 4\epsilon \sin\Delta\phi \sin\gamma, \tag{6}$$

where $r_\pm^2 = 4\mathcal{B}(\pi^0 K^\pm)/[\mathcal{B}(\pi^+ K^0) + \mathcal{B}(\pi^- \bar{K}^0)] = 1.33 \pm 0.45$.

If the SU(3) breaking effect is indeed represented by the last equation in (3), and the tree contribution to $B^\pm \to \pi^\pm K$ is small, information about γ and δ_{EW} obtained are free from uncertainties associated with hadronic matrix elements. Possible SU(3) breaking effects have been estimated and shown to be small [3,4,18]. The smallness of the tree contribution to $B^\pm \to K\pi^\pm$ is true in factorization approximation and can be checked experimentally [19]. The above equations can be tested in the future. We will assume the validity of Eq. (5) and study how information on γ obtained from $B \to K\pi, \pi\pi$ decays depends on δ_{EW}.

The relation between γ and δ_{EW} is complicated. However, it is interesting to note that even in the most general case, bound on $\cos\gamma$ can be obtained. For $\Delta = (r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2) > 0$, we have

$$\cos\gamma \le \delta_{EW} - \frac{\Delta}{2\epsilon(1 + \epsilon\delta_{EW})}, \quad \text{or} \quad \cos\gamma \ge \delta_{EW} - \frac{\Delta}{2\epsilon(-1 + \epsilon\delta_{EW})}. \tag{7}$$

The sign of Δ depends on $r_\pm^2$, ϵ, and δ_{EW}. As long as $r_\pm^2 > 1.07$, Δ is larger than zero at the 90% C.L. in the allowed range for ϵ and any value for δ_{EW}. For smaller $r_\pm^2$, Δ can change sign depending on δ_{EW}. For $\Delta < 0$, the bounds are given by replacing $\le$, $\ge$ by $\ge$, $\le$ in the above equations, respectively. We remark that if $r_\pm^2 < 1$, one can also use the method in Ref. [20] to constrain γ. The above bounds become exact solutions for $\cos\Delta\phi = 1$ and $\cos\Delta\phi = -1$, respectively. For $\epsilon \ll 1$, one obtains the bound $|\cos\gamma - \delta_{EW}| \ge (r_+^2 + r_-^2 - 2)/(4\epsilon)$ in Ref. [3].

We will use the central value for ϵ and vary $r_\pm^2$ in our numerical analysis to illustrate how information on γ and its dependence on new physics through δ_{EW} can be obtained. The bounds on $\cos\gamma$ are shown in Fig. 2 by the solid curves for three representative cases: (a) central values for ϵ and $r_\pm^2$; (b) central values for ϵ and 1σ upper bound $r_\pm^2 = 1.78$; and (c) central value for ϵ and 1σ lower bound $r_\pm^2 = 0.88$. For cases (a) and (b) $\Delta > 0$, and for case (c) $\Delta < 0$.

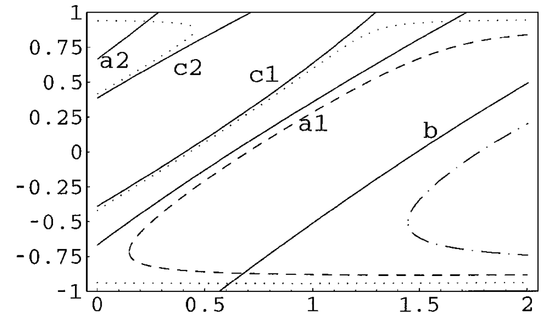

FIG. 2. Bounds on and (solutions for) $\cos\gamma$ vs δ_{EW}. The curves $a1$, $a2$ (dashed line), b (dot-dashed line), and $c1$,$c2$ (dotted line) are the bounds (solutions) on (for) $\cos\gamma$ as functions of δ_{EW} for the three cases (a), (b), and (c) described in the text, respectively.

The bounds with $|\cos\gamma| \le 1$ for (a), (b), and (c) are indicated by the curves ($a1$, $a2$), (b), and ($c1$, $c2$), respectively. For cases (a) and (c) there are two allowed regions, the regions below ($a1$, $c1$) and the regions above ($a2$, $c2$). For case (b) the allowed range is below (b). When $r_\pm^2$ decreases from 1σ upper bound to 1σ lower bound, one of the boundaries goes up from (b) to ($a1$) then moves to ($c2$). And the other boundary for case (b) which is outside the range moves to ($a2$) then goes down to ($c1$). In case (a), for $\delta_{EW} = 0.81(0.65)$ we find $\cos\gamma < 0.18(0.015)$ which is way below the value corresponding to $\cos\gamma_{\text{best}} \approx 0.5$. With $\Delta g_1^Z = 0.126$, $\cos\gamma$ can be close to 0.5. For larger $r_\pm^2$ the situation is worse. This can be seen from the curves for case (b) where $\cos\gamma < 0$ for δ_{EW} up to 1.5. For smaller $r_\pm^2$ the situation is better, as can be seen from case (c). In this case there are larger allowed ranges. $\gamma \approx \gamma_{\text{best}}$ can be accommodated even by the SM.

When the decay amplitudes for $B^\pm \to K\pi$, $B^\pm \to \pi^\pm\pi^0$, and the rate asymmetries for these decays are determined to a good accuracy, γ can be determined using Eq. (3) and its conjugated form. The original method [21] using similar equations without the correction δ_{EW} from electroweak penguin is problematic because the correction is large [22]. Many variations involving other decay modes have been proposed to remove electroweak penguin effects [23]. Recently, it was realized [4] that the difficulties associated with electroweak penguin interaction can be calculated in terms of the quantity δ_{EW}.

This method again crucially depends on the value of δ_{EW}. The solution of $\cos\gamma$ corresponds to the solution of a fourth order polynomial in $\cos\gamma$. Using Eqs. (5) and (6), we have

$$(1 - \cos^2\gamma)\left[1 - \left(\frac{\Delta}{2\epsilon(\delta_{EW} - \cos\gamma)} - \epsilon\delta_{EW}\right)^2\right] - \frac{(r_+^2 - r_-^2)^2}{16\epsilon^2} = 0. \tag{8}$$

The solutions depend on the values of $r_\pm^2$ and ϵ which are not determined with sufficient accuracy at present. To have some idea about the details, we analyze the solutions of $\cos\gamma$ as a function of δ_{EW} for the three cases discussed earlier with a given value for the asymmetry $A_{\text{asy}} = (r_+^2 - r_-^2)/(r_+^2 + r_-^2)$. In Fig. 2 we show the solutions with $A_{\text{asy}} = 15\%$ for illustration. The actual value to be used for practical analysis has to be determined by experiments. The solutions for the three cases (a), (b), and (c) are indicated by the dashed, dot-dashed, and dotted curves in Fig. 2. In general there are four solutions, but not all of them are physical ones satisfying $|\cos\gamma| < 1$.

For case (a), two solutions are allowed with δ_{EW}. To have $\cos\gamma > 0$ δ_{EW} has to be larger than 0.7. Whereas $\cos\gamma \approx \cos\gamma_{\mathrm{best}}$ would require δ_{EW} to be larger than 1.2 which cannot be reached in the SM, but is possible for nonzero Δg_1^Z in its allowed range. With smaller $r_\pm^2$, $\cos\gamma > 0$ can be a solution with smaller δ_{EW} and can even have $\cos\gamma = \cos\gamma_{\mathrm{best}}$. This can be seen from the dotted curves in Fig. 2 for case (c). For larger $r_\pm^2$ in order to have solutions, larger δ_{EW} is required. For case (b) δ_{EW} must be larger than 1.4 in order to have solutions. These regions cannot be reached by SM, nor by the model with Δg_1^Z in the allowed range.

We also analyzed how the solutions change with the asymmetry A_{asy}. With small A_{asy}, the solutions are close to the bounds. When A_{asy} increases, the solutions move away from the bounds. The solutions below the bounds ($a1$), (b), and ($c1$) shift towards the right, and the bounds ($a2$) and ($c2$) move towards the left. In all cases the solutions with $|\cos\gamma| \approx 1$ become more sensitive to δ_{EW} and $|\cos\gamma|$ becomes smaller as A_{asy} increases. In each case discussed the solutions, except the ones close to $|\cos\gamma| = 1$, in models with nonzero Δg_1^Z can be very different from those in the SM. It is clear that important information about γ and about new physics contribution to δ_{EW} can be obtained from $B^\pm \to K\pi, \pi\pi$ decays.

We conclude that the branching ratios of $B \to K\pi$ decays are sensitive to new physics at loop level. The bound on γ, extracted using the central branching ratios for $B^\pm \to K\pi$ and information from $B^\pm \to \pi^\pm\pi$, is different from that obtained from other experimental data. New physics, such as anomalous gauge couplings, can improve the situation. Similar analysis can be applied to any other model where new physics contribute to electroweak penguin interactions. The decay modes, $B^\pm \to K\pi, \pi\pi$ will be measured at various B factories with improved error bars. The standard model and models beyond will be tested in the near future.

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