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$B \to \pi K$ puzzle and new physics

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The present $B \to \pi K$ data is studied in the context of the standard model (SM) and with new physics (NP). We confirm that the SM has difficulties explaining the $B \to \pi K$ measurements. By adopting an effective-lagrangian parametrization of NP effects, we are able to rule out several classes of NP. Our model-independent analysis shows that the $B \to \pi K$ data can be accommodated by NP in the electroweak penguin sector.

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The B-factories BaBar and Belle have measured (most of) the branching ratios and CP asymmetries for the various $B \to \pi\pi$ and $B \to \pi K$ decays, and these can be used to search for physics beyond the standard model (SM). By using flavor SU(3) symmetry to relate these processes [1–6], several analyses were able to constrain the SM parameters, and to look for signs of New Physics (NP). The advantage of this approach is that one takes into account a large number of processes. The disadvantage is that one has to deal with unknown effects related to the breaking of SU(3) symmetry. Also, $B \to \pi\pi$ decays involve the quark-level processes $\bar{b} \to \bar{d} q \bar{q}$ $(q = u, d)$, while $B \to \pi K$ receives contributions from $\bar{b} \to \bar{s} q \bar{q}$. If there is NP, it could affect $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ processes differently.

For this reason, there are advantages to considering $B \to \pi K$ decays alone. As we will see, these processes contain enough information to constrain the SM parameters. Within the diagrammatic approach [7], the amplitudes for the four $B \to \pi K$ decays can be written in terms of seven diagrams: the color-favored and color-suppressed tree amplitudes T' and C', the gluonic penguin amplitudes P' and P'_{uc}, the color-favored and color-suppressed electroweak penguin amplitudes P'_{EW} and P'^{C}_{EW}, and the annihilation amplitude A'. (The primes on the amplitudes indicate $\bar{b} \to \bar{s}$ transitions.)

In Ref. [7], the relative sizes of the amplitudes were roughly estimated as

$$\begin{gathered} 1 : |P'|, \qquad \mathcal{O}(\bar{\lambda}) : |T'|, |P'_{EW}|, \\ \mathcal{O}(\bar{\lambda}^2) : |C'|, |P'_{uc}|, |P'^{C}_{EW}|, \qquad \mathcal{O}(\bar{\lambda}^3) : |A'|, \end{gathered} \tag{1}$$

where $\bar{\lambda} \sim 0.2$. These estimates are expected to hold approximately in the SM. Thus, to $O(\bar{\lambda})$, we can ignore all diagrams but P', T' and P'_{EW} in our $B \to \pi K$ amplitudes. We will perform a fit of the present $B \to \pi K$ data—the goodness or badness of the fit should not be much affected by the inclusion of the smaller amplitudes.

The four amplitudes can then be written as

$$\begin{aligned} A(B^+ \to \pi^+ K^0) &\equiv A^{+0} = -P', \\ \sqrt{2}A(B^+ \to \pi^0 K^+) &\equiv \sqrt{2}A^{0+} = -T' e^{i\gamma} + P' - P'_{EW}, \\ A(B^0 \to \pi^- K^+) &\equiv A^{-+} = -T' e^{i\gamma} + P', \\ \sqrt{2}A(B^0 \to \pi^0 K^0) &\equiv \sqrt{2}A^{00} = -P' - P'_{EW}, \end{aligned} \tag{2}$$

where we have explicitly written the dependence on the weak phase (including the minus sign from $V^*_{tb}V_{ts}$ $[P']$), while the amplitudes contain strong phases. (The phase information in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix is conventionally parametrized in terms of the unitarity triangle, in which the interior (CP-violating) angles are known as α, β and γ [8].)

We have one additional piece of information: within the SM, to a good approximation, the diagram P'_{EW} can be related to T' using flavor SU(3) [9]:

$$P'_{EW} \simeq \frac{3}{4}\left[\frac{c_9 + c_{10}}{c_1 + c_2} + \frac{c_9 - c_{10}}{c_1 - c_2}\right] R T'. \tag{3}$$

Here, the c_i are Wilson coefficients [10] and

$$R \equiv \left| \frac{V^*_{tb}V_{ts}}{V^*_{ub}V_{us}} \right| = \frac{1}{\lambda^2}\frac{\sin(\beta + \gamma)}{\sin\beta}. \tag{4}$$

With the above relation, the $B \to \pi K$ observables contain five theoretical parameters: $|P'|$, $|T'|$, β, γ, and one relative strong phase, δ. The phase β can be taken from the measurement of $\sin 2\beta$ in $B^0_d(t) \to J/\psi K_S$: $\sin 2\beta = 0.726 \pm 0.037$ [11], leaving four theoretical unknowns. However, there are a total of nine $B \to \pi K$ measurements: four CP-averaged branching ratios and five CP asymmetries (Table 1, [12]). Within the parametrization of Eq. (2), three of these are independent of the theoretical parameters: the direct CP asymmetries in $B^+ \to \pi^+ K^0$ and $B^0 \to \pi^0 K^0$ are predicted to vanish, and the indirect CP asymmetry in $B^0 \to \pi^0 K^0$ measures $\sin 2\beta$. The remaining six observables are functions of the four theoretical parameters, so we can perform a fit to obtain these quantities.

Using the parametrization of Eq. (2) for the $B \to \pi K$ amplitudes, we find that $\chi^2_{\rm min}/d.o.f. = 15.6/5$ (0.8%), indicating a very poor fit. (The number in parentheses indicates the quality of the fit, and depends on $\chi^2_{\rm min}$ and $d.o.f.$ individually. 50% is a good fit; fits which are substantially less than 50% are poorer.) This is not a new result—other analyses have made a similar observation [1,3–6]. It shows that present data is inconsistent with the naive implementation of the SM. Our parametrization is therefore incomplete. There are two ways to make modifications. Either we work within the SM, or we add new physics. We address these possibilities in turn.

We begin with the SM, but abandon the relation between P'_{EW} and T' [Eq. (3)]. We now have six theoretical parameters: $|P'|$, $|T'|$, $|P'_{EW}|$, γ, and two relative strong phases. In this case, the fit is good: $\chi^2_{\rm min}/d.o.f. = 2.7/3$ (44%). The fit also gives a central value of $\gamma = 59°$. This is consistent with the value of γ obtained via a fit to independent measurements: $\gamma = 62^{+10}_{-12}{}°$ [13]. (Because these errors are not gaussian, we do not include this information in our fit at this stage.) On the other hand, the fit also gives $|P'_{EW}/T'| = 1.55 \pm 0.68$, whose central value is far from its SM value of 0.65 ± 0.15 [9]. Thus, while it is possible to explain the present $B \to \pi K$ data by treating P'_{EW} and T' independently, it is difficult to understand how $|P'_{EW}/T'|$ could be so much larger than its SM value.

The second modification is to take into account the smaller (neglected) amplitudes. Including the $O(\bar{\lambda}^2)$ diagrams, the $B \to \pi K$ amplitudes take the form

$$\begin{aligned}
A^{+0} &= -P' + P'_{uc} e^{i\gamma} - \frac{1}{3} P'^C_{EW}, \\
\sqrt{2} A^{0+} &= -T' e^{i\gamma} - C' e^{i\gamma} + P' - P'_{uc} e^{i\gamma} - P'_{EW} - \frac{2}{3} P'^C_{EW}, \\
A^{-+} &= -T' e^{i\gamma} + P' - P'_{uc} e^{i\gamma} - \frac{2}{3} P'^C_{EW}, \\
\sqrt{2} A^{00} &= -C' e^{i\gamma} - P' + P'_{uc} e^{i\gamma} - P'_{EW} - \frac{1}{3} P'^C_{EW}.
\end{aligned} \qquad (5)$$

In this case, P'^C_{EW} is not independent of the amplitudes T' and C'. We have [9]

$$\begin{aligned}
P'_{EW} &= \frac{3}{4} \frac{c_9 + c_{10}}{c_1 + c_2} R(T' + C') + \frac{3}{4} \frac{c_9 - c_{10}}{c_1 - c_2} R(T' - C'), \\
P'^C_{EW} &= \frac{3}{4} \frac{c_9 + c_{10}}{c_1 + c_2} R(T' + C') - \frac{3}{4} \frac{c_9 - c_{10}}{c_1 - c_2} R(T' - C').
\end{aligned} \qquad (6)$$

With these relations, we now have eight theoretical parameters: $|P'|$, $|P'_{uc}|$, $|T'|$, $|C'|$, γ, and three relative strong phases. With nine pieces of experimental data, we can still perform a fit, which is acceptable: $\chi^2_{\rm min}/d.o.f. = 0.7/1$ (40%). In addition, we find $\gamma = 64°$, consistent with independent measurements. However, the fit gives $|C'/T'| = 1.8 \pm 1.0$, whose central value is far larger than naive estimates. Other analyses have also found the C' must be very big to explain the $B \to \pi K$ data [5,6]. In Ref. [6], it is argued that final-state interactions (FSI) can increase the size of C'. However, in that case, the authors were attempting to explain $|C'/T'| \simeq 0.5$ (which comes from the joint fit to $B \to \pi K$ and $B \to \pi\pi$ decays [2]). Even with FSI, it is difficult to see how C' can be increased to about twice as large as T'.

TABLE I. Branching ratios, direct CP asymmetries $A_{\rm dir}$, and mixing-induced CP asymmetry $A_{\rm indir}$ (if applicable) for the four $B \to \pi K$ decay modes.

Mode	$BR(10^{-6})$	$A_{\rm dir}$	$A_{\rm indir}$
$B^+ \to \pi^+ K^0$	24.1 ± 1.3	-0.020 ± 0.034	
$B^+ \to \pi^0 K^+$	12.1 ± 0.8	0.04 ± 0.04	
$B^0_d \to \pi^- K^+$	18.2 ± 0.8	-0.109 ± 0.019	
$B^0_d \to \pi^0 K^0$	11.5 ± 1.0	-0.09 ± 0.14	0.34 ± 0.28

It is therefore extremely difficult to explain the current $B \to \pi K$ data within the SM alone. Instead, one must consider the effect of new-physics operators. These can be included in B-physics analyses in a model-independent way [14]. We suppose that there are NP contributions to $\bar{b} \to \bar{s} q \bar{q}$ transitions which are roughly the same size as the SM $\bar{b} \to \bar{s}$ penguin operators. The NP contributions take the form $\mathcal{O}^{ij,q}_{NP} \sim \bar{s}\Gamma_i b \bar{q} \Gamma_j q$ ($q = u, d, s, c$), where the $\Gamma_{i,j}$ represent Lorentz structures, and color indices are suppressed. There are a total of 20 possible NP operators, each of which can in principle have a different weak phase. The NP contributes to the decay $B \to f$ through its matrix elements $\langle f | \mathcal{O}^{ij,q}_{NP} | B \rangle$, which can be written as

$$\langle f | \mathcal{O}^{ij,q}_{NP} | B \rangle = A_k e^{i\phi^q_k} e^{i\delta^q_k}, \qquad (7)$$

where ϕ^q_k and δ^q_k are the NP weak and strong phases associated with the individual matrix elements. However, the key point is that the NP strong phases are very small. The reasoning goes as follows. Strong phases arise from rescattering. In the SM, the (large) tree diagram ($\tilde{T}'$) $\bar{b} \to \bar{s} c \bar{c}$ can rescatter into the c-quark penguin P'_c, possibly giving it a strong phase of $O(1)$. Note that $|P'_c/\tilde{T}'| \lesssim 10\%$. That is, in the SM the diagram responsible for the rescattering is considerably larger than the diagram which receives the strong phase. On the other hand, the NP rescattering can only come from the NP matrix elements themselves. Assuming the same suppression factor, the NP strong phases are $O(10\%)$, which is negligible, to a good approximation. Note that this is a quite general result and applies to all NP models.

The neglect of NP strong phases allows for a great simplification. For a given type of transition, all NP matrix elements can now be combined into a single NP amplitude, with a single weak phase:

$$\sum \langle f | \mathcal{O}^{ij,q}_{NP} | B \rangle = \mathcal{A}^q e^{i\Phi_q}, \qquad (8)$$

where $q = u, d, s, c$. (Throughout the paper, the symbols $\mathcal{A}$ and Φ denote the NP amplitudes and weak phases, respectively.) $B \to \pi K$ decays involve only NP parameters related to the quarks u and d. These operators come in two classes, differing in their color structure: $\bar{s}_\alpha \Gamma_i b_\alpha \bar{q}_\beta \Gamma_j q_\beta$ and $\bar{s}_\alpha \Gamma_i b_\beta \bar{q}_\beta \Gamma_j q_\alpha$ $(q = u, d)$. The matrix elements of these operators can be combined into single NP amplitudes, denoted $\mathcal{A}'^{,q} e^{i\Phi'_q}$ and $\mathcal{A}'^{C,q} e^{i\Phi'^C_q}$, respectively [15]. Here, Φ'_q and Φ'^C_q are the NP weak phases; the strong phases are zero. Each of these contributes differently to the various $B \to \pi K$ decays. In general, $\mathcal{A}'^{,q} \neq \mathcal{A}'^{C,q}$ and $\Phi'_q \neq \Phi'^C_q$. Note that, despite the "color-suppressed" index C, the matrix elements $\mathcal{A}'^{C,q} e^{i\Phi'^C_q}$ are not necessarily smaller than the $\mathcal{A}'^{,q} e^{i\Phi'_q}$.

The $B \to \pi K$ amplitudes can now be written in terms of the SM amplitudes to $O(\bar{\lambda})$ [P'_{EW} and T' are related as in Eq. (3)], along with the NP matrix elements [15]:

$$
\begin{aligned}
A^{+0} &= -P' + \mathcal{A}'^{C,d} e^{i\Phi'^C_d}, \\
\sqrt{2}A^{0+} &= P' - T' e^{i\gamma} - P'_{EW} + \mathcal{A}'^{,comb} e^{i\Phi'} - \mathcal{A}'^{C,u} e^{i\Phi'^C_u}, \\
A^{-+} &= P' - T' e^{i\gamma} - \mathcal{A}'^{C,u} e^{i\Phi'^C_u}, \\
\sqrt{2}A^{00} &= -P' - P'_{EW} + \mathcal{A}'^{,comb} e^{i\Phi'} + \mathcal{A}'^{C,d} e^{i\Phi'^C_d}, \qquad (9)
\end{aligned}
$$

where $\mathcal{A}'^{,\mathrm{comb}} e^{i\Phi'} \equiv -\mathcal{A}'^{,u} e^{i\Phi'_u} + \mathcal{A}'^{,d} e^{i\Phi'_d}$. There are now a total of 11 theoretical parameters: $|P'|$, $|T'|$, $|\mathcal{A}'^{,\mathrm{comb}}|$, $|\mathcal{A}'^{C,u}|$, $|\mathcal{A}'^{C,d}|$, γ, 3 NP weak phases and two relative strong phases. With only 9 experimental measurements, it is not possible to perform a fit. It is necessary to make some theoretical assumptions.

We assume that a single NP amplitude dominates. There are an infinite number of choices, but we consider the following four possibilities: (i) only $\mathcal{A}'^{,\mathrm{comb}} \neq 0$, (ii) only $\mathcal{A}'^{C,u} \neq 0$, (iii) only $\mathcal{A}'^{C,d} \neq 0$, (iv) $\mathcal{A}'^{C,u} e^{i\Phi'^C_u} = \mathcal{A}'^{C,d} e^{i\Phi'^C_d}$, $\mathcal{A}'^{,\mathrm{comb}} = 0$ (isospin-conserving NP).

In the first three cases there are seven parameters: three amplitude magnitudes, γ, one weak NP phase and two relative strong phases. However, for the type of NP characterizing the fourth fit, all $B \to \pi K$ amplitudes and their CP-conjugates contain two combinations of amplitudes. These can be written as follows:

$$
\begin{aligned}
P_{NP} e^{i\delta_{NP}} e^{i\Phi_{NP}} &= -P' + \mathcal{A}'^{C,d} e^{i\Phi'^C_d}, \\
\bar{P}_{NP} e^{i\delta_{NP}} e^{-i\Phi_{NP}} &= -P' + \mathcal{A}'^{C,d} e^{-i\Phi'^C_d},
\end{aligned} \qquad (10)
$$

with $P_{NP} \neq \bar{P}_{NP}$. However, note that the real parts of these quantities are equal: $P_{NP} \cos(\delta_{NP} + \Phi_{NP}) = \bar{P}_{NP} \cos(\delta_{NP} - \Phi_{NP})$. Thus, one variable, say δ_{NP}, can be written as a function of the other three. That is, in this case there is one fewer degree of freedom, and the $B \to \pi K$ amplitudes contain six unknown parameters: P_{NP}, $\bar{P}_{NP}$, T', γ, Φ_{NP} and $\delta_{T'}$.

In cases (i), (iii) and (iv), there are more measurements than unknowns, and we can perform a fit. On the other hand, parametrization (ii) makes the same predictions as the SM: $A_{\mathrm{dir}}(B^+ \to \pi^+ K^0) = A_{\mathrm{dir}}(B^0 \to \pi^0 K^0) = 0$ and $A_{\mathrm{indir}}(B^0 \to \pi^0 K^0) = \sin 2\beta$. Thus, in this case, there are only six observables, and we cannot determine the seven theoretical parameters.

Using Table I, our results are: (i) $\chi^2_{\mathrm{min}}/d.o.f. = 1.9/2$ (39%), (iii) $\chi^2_{\mathrm{min}}/d.o.f. = 9.4/2$ 0.9%), (iv) $\chi^2_{\mathrm{min}}/d.o.f. = 3.9/3$ (27%). Thus, based on the fit quality only, we conclude that fit (i) is acceptable, fit (iv) is somewhat less good, and fit (iii) is poor.

However, these fits also give values for the CP angle γ: (i) $\gamma = 64.2°$, (iii) $\gamma = 31.8°$, (iv) $\gamma = 37.8°$. These can be compared with the value obtained from a fit to independent data, $\gamma = 62^{+10}_{-12}{}°$ [13]. Note that this latter value of γ includes limits on B^0_s–$\bar{B}^0_s$ mixing. However, the NP considered here will, in general, also lead to effects in this mixing. Thus, technically, in considering this type of NP, the B^0_s–$\bar{B}^0_s$ mixing data should be removed from the γ fit. In practice, though, this will not make much difference. We therefore continue to use the best-fit values of γ with $\gamma = 62^{+10}_{-12}{}°$ as the independent value, but the reader should keep this caveat in mind.

Note also that any explanation of the $B \to \pi K$ data using new physics must also reproduce the SM value of γ. This demonstrates that, in looking for NP, it is important to use all handles available, and not simply concentrate on measurements of the CP phases.

We incorporate the information on γ by adding a constraint to the data, so that we now fit to all the $B \to \pi K$ data and $\gamma = 62 \pm 11°$. (Note that the γ constraint is not a true experimental number—it has some theoretical input—and so its inclusion in the fit must be viewed with some prudence.) With this added input, we can now perform a fit in parametrization (ii). We find: (i) $\chi^2_{\mathrm{min}}/d.o.f. = 1.9/3$ (59%), (ii) $\chi^2_{\mathrm{min}}/d.o.f. = 2.7/3$ (44%), (iii) $\chi^2_{\mathrm{min}}/d.o.f. = 9.4/3$ (2%), (iv) $\chi^2_{\mathrm{min}}/d.o.f. = 6.7/4$ (15%). We conclude that fits (i) and (ii) are good, while fit (iv) is poorer, and fit (iii) is very poor. We do not consider fit (iii) further.

However, we have still not included all the information at our disposal. In the fits, we find that (i) $\delta_{T'} = -58.4°$, (ii) $\delta_{T'} = -26.2°$ or $68.8°$, and (iv) $\delta_{T'} = -47°$. On the other hand, the diagram T' is governed by the CKM matrix elements $V^*_{ub} V_{us}$, and so its strong phase can arise only from self-rescattering. Thus, like the new-physics amplitudes, the strong phase of T', $\delta_{T'}$, is expected to be very small. This requirement gives us an additional handle. We incorporate this by adding a constraint to the data: we require $\delta_{T'} = 0 \pm 10°$. Since this is purely theoretical, it is obviously not on the same footing as the $B \to \pi K$ data. However, since we only want to see if particular NP models give a good fit, it is sensible to include this information among the constraints.

Including the constraint on $\delta_{T'}$, we find (i) $\chi^2_{\mathrm{min}}/d.o.f. = 2.2/4$ (70%), (ii) $\chi^2_{\mathrm{min}}/d.o.f. = 5.9/4$ (21%), and (iv) $\chi^2_{\mathrm{min}}/d.o.f. = 14.3/5$ (1%). We therefore find that (i) is a good fit, (ii) is poorer, and (iv) is a very poor fit.

Of the four new-physics models examined in this paper, only one produces a good fit to the $B \to \pi K$ data and the various imposed constraints on γ and $\delta_{T'}$. It is case (i), $\mathcal{A}'^{,\text{comb}} \neq 0$. In this model, the best-fit values of the theoretical parameters are $|T'/P'| = 0.22$ (in line with theoretical expectations), $|\mathcal{A}'^{,\text{comb}}/P'| = 0.36$, $\Phi' = 100°$, $\delta_{P'} = -10°$. We therefore find that the NP amplitude must be sizeable, with a large weak phase.

This class of NP models essentially corresponds to a modification of the SM electroweak penguin amplitude, as explored in Refs. [1,4,16]. In Ref. [1] the weak phase of the electroweak penguin was modified, meaning that the NP operator is of the form $(V - A) \times (V - A)$. Here, we allow any form for the operator, so that this is a more general solution. NP models which can lead to this include Z- and Z'-mediated flavour-changing neutral currents [16,17] or supersymmetry with R-parity breaking.

Fit (ii) ($\mathcal{A}'^{C,u} \neq 0$) is poorer, but not ruled out (though it does give a value for $|T'/P'|$ which is about 3 times larger than expectations). This is a NP solution which has not been considered before. It can arise, for example, in supersymmetric models with R-parity breaking. Fit (iii) ($\mathcal{A}'^{C,d} \neq 0$) yields a poor fit, so that this class of NP models is (close to) ruled out. We also rule out isospin-conserving models of NP [fit (iv)]. These include new physics whose principal effect is to generate an anomalous gluonic quadrupole moment [18].

A word of caution: one has to be careful about ruling out particular models of new physics. Any specific NP model will, in general, lead to more than one effective NP operator, and the more general case can be used to explain the $B \to \pi K$ data.

To summarize, we have presented a study of the current $B \to \pi K$ data. The standard model (SM) has great difficulty accounting for these measurements. Depending on the parametrization, one obtains a poor fit, or values for the SM parameters which are greatly at odds with our present understanding. For models of new physics , we adopt a model-independent, effective-lagrangian parametrization of the NP effects. There are three possible (complex) NP parameters which can affect $B \to \pi K$ decays, denoted $\mathcal{A}'^{,\text{comb}}$, $\mathcal{A}'^{C,u}$ and $\mathcal{A}'^{C,d}$. We consider four classes of NP models: (i) only $\mathcal{A}'^{,\text{comb}} \neq 0$, (ii) only $\mathcal{A}'^{C,u} \neq 0$, (iii) only $\mathcal{A}'^{C,d} \neq 0$, (iv) isospin-conserving NP: $\mathcal{A}'^{C,u} e^{i\Phi_u'^C} = \mathcal{A}'^{C,d} e^{i\Phi_d'^C}$, $\mathcal{A}'^{,\text{comb}} = 0$. Of these, the classes of models (ii), (iii) and (iv) produce poor or very poor fits. Only model (i) explains the data satisfactorily. It corresponds to a modification of the electroweak penguin (EWP) amplitude. Note that, while other studies also consider specific models of NP in the EWP, our analysis is completely model independent.

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