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Determining weak phases from the $B \to \pi\pi$, $K\pi$ decays

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Recent data of two-body nonleptonic B meson decays allow a topological-amplitude analysis up to the $O(\lambda^2)$ accuracy, where λ denotes the Wolfenstein parameter. We find an exact solution from the $B \to \pi\pi$ data and an exact solution from the $B \to K\pi$ data, which satisfy the approximate SU(3) flavor symmetry. These solutions indicate that the color-suppressed tree amplitude is large, all other amplitudes can be understood within the standard-model, and the weak phases $\phi_2 \approx 90^o$ and $\phi_3 \approx 60^o$ are consistent with the global unitarity triangle fit.

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To determine the weak phases in the Kobayashi-Maskawa ansatz for CP violation [1], one either resorts to theoretically clean modes, which are usually experimentally difficult, or to the modes with higher feasibility, which, however, require theoretical inputs [2]. Recently, we have adopted the topological-amplitude parametrization for two-body nonleptonic B meson decays, in which the theoretical inputs are the counting rules for various decay amplitudes [3] in terms of powers of the Wolfenstein parameter $\lambda \sim 0.22$. These counting rules are supported by the known QCD theories [4–7], and slightly different from those postulated in [8]. The strategy of this method is to drop the topologies with higher powers of λ until the number of free parameters are equal to the number of available measurements. The weak phases and the amplitudes are then solved exactly by comparing the resultant parametrization with experimental data. Afterwards, it should be examined whether the obtained amplitudes obey the power counting rules. If they do, the extracted weak phases suffer only the theoretical uncertainty from the neglected topologies. If not, the inconsistency could be regarded as a warning to the QCD theories.

Because the data were not complete, the analysis performed in [2] was limited to the $O(\lambda)$ accuracy: the electroweak penguin amplitude P_{ew} has been neglected for the $B \to \pi\pi$ decays. The color-suppressed tree amplitude C, the color-suppressed electroweak penguin amplitude P^c_{ew}, and the tree annihilation amplitude T^a have been neglected for the $B \to K\pi$ decays. In this work we shall improve the accuracy up to $O(\lambda^2)$, since recent experimental progress has allowed this study. Moreover, we shall look for the solutions, in which the amplitudes of each topology from the $B \to \pi\pi$, $K\pi$ modes are consistent with the approximate SU(3) flavor symmetry. If such solutions exist (there is no guarantee for the existence in this method), all the above data can be understood in a consistent way, and the determination of the weak phases ϕ_2 and ϕ_3 will be convincing. The $B \to \pi\pi$, $K\pi$ old data have been investigated in [9,10] based on the SU(3) flavor symmetry to some extent, and an extracted large P_{ew} has been claimed to signal new physics. We shall point out that the large P_{ew} is a consequence of the *strong* assumption of the SU(3) flavor symmetry and of the old data. Different prescriptions for taking into account SU(3) symmetry breaking effects have led to different extractions of amplitudes [9–11], while our exact solutions avoid this ambiguity. As shown below, the new data in fact imply only a large C, and all other amplitudes, including P_{ew}, can be understood within the standard-model.

The most general topological-amplitude parametrization of the $B \to \pi\pi$ decay amplitudes is written as

$$\begin{aligned}\sqrt{2}A(B^+ \to \pi^+\pi^0) &= -T\left[1 + \frac{C}{T} + \frac{P_{ew}}{T}e^{i\phi_2}\right],\\ A(B_d^0 \to \pi^+\pi^-) &= -T\left(1 + \frac{P}{T}e^{i\phi_2}\right),\\ \sqrt{2}A(B_d^0 \to \pi^0\pi^0) &= T\left[\left(\frac{P}{T} - \frac{P_{ew}}{T}\right)e^{i\phi_2} - \frac{C}{T}\right],\end{aligned} \quad (1)$$

with the power counting rules,

$$\frac{P}{T} \sim \lambda, \frac{C}{T} \sim \lambda, \frac{P_{ew}}{T} \sim \lambda^2. \quad (2)$$

We have adopted the t-convention for the above parametrization with the product of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $V_c = V_{cd}V^*_{cb}$ being eliminated by virtue of the unitarity relation. In this convention the tree amplitudes contain the weak phase ϕ_3, and the penguin amplitudes contain ϕ_1. ϕ_3 is then factored out, such that the penguin amplitudes carry the weak phase $\phi_2 = 180^o - \phi_1 - \phi_3$ eventually. There are 4 independent amplitudes, namely, 7 parameters, because an overall phase can always be removed. Including the weak phase ϕ_2, there are 8 unknowns in Eq. (1). The available data of the branching ratios and the CP asymmetries are summarized as [12],

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$$\begin{aligned}
&\mathrm{Br}(B^\pm \to \pi^\pm\pi^0) = (5.5 \pm 0.6)\times 10^{-6}(\text{updated}), \quad \mathrm{Br}(B_d^0 \to \pi^\pm\pi^\mp) = (4.6 \pm 0.4)\times 10^{-6},\\
&\mathrm{Br}(B_d^0 \to \pi^0\pi^0) = (1.51 \pm 0.28)\times 10^{-6}(\text{updated}), \quad \mathcal{A}(B_d^0 \to \pi^\pm\pi^\mp) = (37 \pm 11)\%(\text{updated}),\\
&S(B_d^0 \to \pi^\pm\pi^\mp) = -(61 \pm 14)\%(\text{updated}), \quad \mathcal{A}(B^\pm \to \pi^\pm\pi^0) = -(1 \pm 7)\%(\text{new}),\\
&\mathcal{A}(B_d^0 \to \pi^0\pi^0) = (28 \pm 39)\%(\text{new}).
\end{aligned} \tag{3}$$

Following [2], the parametrization for the $B \to K\pi$ decays is written, up to $O(\lambda^2)$, as

$$\begin{aligned}
&A(B^+ \to K^0\pi^+) = P', \quad A(B_d^0 \to K^+\pi^-) = -P'\left(1 + \frac{T'}{P'}e^{i\phi_3}\right),\\
&\sqrt{2}A(B^+ \to K^+\pi^0) = -P'\left[1 + \frac{P'_{ew}}{P'} + \left(\frac{T'}{P'} + \frac{C'}{P'}\right)e^{i\phi_3}\right], \quad \sqrt{2}A(B_d^0 \to K^0\pi^0) = P'\left(1 - \frac{P'_{ew}}{P'} - \frac{C'}{P'}e^{i\phi_3}\right),
\end{aligned} \tag{4}$$

with the power counting rules,

$$\frac{T'}{P'} \sim \lambda, \frac{P'_{ew}}{P'} \sim \lambda, \frac{C'}{P'} \sim \lambda^2. \tag{5}$$

There are also 8 unknowns including the weak phase ϕ_3, which will be solved from the 8 experimental inputs [12],

$$\begin{aligned}
&\mathrm{Br}(B^\pm \to K^0\pi^\pm) = (24.1 \pm 1.3)\times 10^{-6}(\text{updated}), \quad \mathrm{Br}(B_d^0 \to K^\pm\pi^\mp) = (18.2 \pm 0.8)\times 10^{-6},\\
&\mathrm{Br}(B^\pm \to K^\pm\pi^0) = (12.1 \pm 0.8)\times 10^{-6}(\text{updated}), \quad \mathrm{Br}(B_d^0 \to K^0\pi^0) = (11.5 \pm 1.0)\times 10^{-6},\\
&\mathcal{A}(B_d^0 \to K^\pm\pi^\pm) = -(11.3 \pm 1.9)\%(\text{updated}), \quad \mathcal{A}(B^\pm \to K^\pm\pi^0) = (4 \pm 4)\%(\text{updated}),\\
&\mathcal{A}(B_d^0 \to K^0\pi^0) = (9 \pm 14)\%(\text{new}), \quad S(B_d^0 \to K_S\pi^0) = (34^{+27}_{-29})\%(\text{new}).
\end{aligned} \tag{6}$$

The weak phase ϕ_1 is set to 23^o from the time-dependent $B \to J/\psi K^{(*)}$ measurement. Plus the unitarity relation among the weak phases, all the above (primed and unprimed) amplitudes, ϕ_2 and ϕ_3 can be solved exactly.

Neglecting the $O(\lambda^2)$ terms in the above parametrizations, more than one $O(\lambda)$ solutions have been obtained excluding the data labeled by "new" [2]. Some $O(\lambda)$ solutions from the $B \to \pi\pi$ data favor an amplitude C, which is large and constructive to T, but some do not. Including the new data, we are allowed to improve the accuracy up to $O(\lambda^2)$, at which the approximate SU(3) flavor symmetry relations,

$$\frac{P}{T} \approx \frac{P'}{T'}\epsilon e^{i\phi_1}, \quad \frac{C}{T} \approx \frac{C'}{T'}, \quad \frac{P_{ew}}{P} \approx \frac{P'_{ew}}{P'}, \tag{7}$$

with the factor $\epsilon \equiv \lambda^2/(1-\lambda^2) = 0.05$, come to help discriminate different solutions. This discrimination is impossible at $O(\lambda)$, since P_{ew} (C') does not appear in the $O(\lambda)$ parametrization for the $\pi\pi$ ($K\pi$) modes. We argue, as pointed out in [13,14], that it is unreasonable to apply the exact SU(3) flavor symmetry to relate the amplitudes in the $\pi\pi$, $K\pi$ modes. On one hand, the symmetry must be broken by QCD dynamics. On the other hand, the amplitudes in Eqs. (1) and (4) have absorbed some subleading contributions through their redefinitions. To be explicit, we have, even under the exact SU(3) flavor symmetry,

$$\begin{aligned}
&T - T' = T^a, \quad C - C' = -T^a,\\
&P - P' = P^a_{ew}, \quad P_{ew} - P'_{ew} = P^c_{ew},
\end{aligned} \tag{8}$$

with the electroweak penguin annihilation amplitude P^a_{ew}. According to the power counting rules in [2], C/T and C'/T' could differ by $O(\lambda) \sim 20\%$, and P_{ew}/P and P'_{ew}/P' could differ by $O(\lambda^2) \sim 5\%$. Adding the SU(3) symmetry breaking effect about 20%–30%, we assume that Eq. (7) may suffer corrections of order 30%–50%.

Considering only the central values of the data as a demonstration, there are four exact solutions for the $K\pi$ modes:

$$\begin{aligned}
&\frac{T'}{P'} = 0.30e^{-170^o i}, \quad \frac{P'_{ew}}{P'} = 0.13e^{7^o i},\\
&\frac{C'}{T'} = 0.89e^{-24^o i}, \quad \phi_3 = 63^o,
\end{aligned} \tag{9}$$

$$\begin{aligned}
&\frac{T'}{P'} = 0.38e^{-8^o i}, \quad \frac{P'_{ew}}{P'} = 0.42e^{93^o i},\\
&\frac{C'}{T'} = 0.69e^{155^o i}, \quad \phi_3 = 116^o,
\end{aligned} \tag{10}$$

$$\begin{aligned}
&\frac{T'}{P'} = 0.55e^{-5^o i}, \quad \frac{P'_{ew}}{P'} = 0.46e^{-90^o i},\\
&\frac{C'}{T'} = 0.47e^{-160^o i}, \quad \phi_3 = 116^o,
\end{aligned} \tag{11}$$

$$\begin{aligned}
&\frac{T'}{P'} = 0.85e^{-176^o i}, \quad \frac{P'_{ew}}{P'} = 0.10e^{-163^o i},\\
&\frac{C'}{T'} = 1.18e^{-179^o i}, \quad \phi_3 = 58^o.
\end{aligned} \tag{12}$$

Other solutions with $T'/P' > 1$ or with all the phases different from those in Eqs. (9)–(12) by 180^o have been suppressed. We have varied the data slightly around their central values, and found that the above solutions are stable. Equation (11), showing a large P'_{ew}/P', is close to that obtained from the $O(\lambda)$ analysis [2], which is valid for a smaller C'. The other three with larger C'/T' are new, and can not be derived at $O(\lambda)$. We then input the above ϕ_3 values into the $B \to \pi\pi$ case, and look for solutions satisfying Eq. (7). Substituting $\phi_2 = 180^o - \phi_1 - \phi_3 \sim 40^o$ from Eqs. (10) and (11) into Eq. (1), we find no solution, indicating that Eqs. (10) and (11) can not be the consistent solutions for both the $\pi\pi$ and $K\pi$ modes. In fact, ϕ_2 must be greater than 60^o in order for a solution to exist. That is, the current $B \to \pi\pi$ data have imposed a constraint on the allowed range of ϕ_2. The phase $\phi_2 \sim 90^o$ corresponding to Eqs. (9) and (12) gives four solutions,

$$\frac{P}{T} = 0.41e^{150^o i}, \quad \frac{C}{T} = 0.81e^{-55^o i}, \quad \frac{P_{ew}}{P} = 0.18e^{12^o i}, \tag{13}$$

$$\frac{P}{T} = 0.41e^{150^o i}, \quad \frac{C}{T} = 0.77e^{-50^o i}, \quad \frac{P_{ew}}{P} = 0.03e^{145^o i}, \tag{14}$$

$$\frac{P}{T} = 0.41e^{150^o i}, \quad \frac{C}{T} = 0.42e^{60^o i}, \quad \frac{P_{ew}}{P} = 2.41e^{47^o i}, \tag{15}$$

$$\frac{P}{T} = 0.41e^{150^o i}, \quad \frac{C}{T} = 0.34e^{58^o i}, \quad \frac{P_{ew}}{P} = 2.56e^{44^o i}. \tag{16}$$

It is easy to observe that only Eq. (13) obeys the approximate relations to Eq. (9) shown in Eq. (7): C/T in Eq. (13) differs from C'/T' in Eq. (9) by $2|C/T - C'/T'|/(|C/T| + |C'/T'|) \sim 50\%$, and P_{ew}/P differs from P'_{ew}/P' by about 30%. For Eq. (14), the direction of P_{ew}/P is almost opposite to that of P'_{ew}/P' in Eq. (9). For Eqs. (15) and (16), the magnitude of P_{ew}/P is too much larger than that of P'_{ew}/P', and C/T also dramatically differs from C'/T'. Equation (12) is not favored, since none of Eqs. (13)–(16) is close to it. As emphasized before, a consistency like the one between Eqs. (9) and (13) means that the $B \to \pi\pi$, $K\pi$ data are really consistent with each other! Note that Eqs. (9) and (13) correspond to the central values of the data. If considering the allowed range, the two solutions can be even closer.

We conclude from our $O(\lambda^2)$ analysis:

(i) The extracted ratio T'/P' in Eq. (9) is in agreement with the theoretical prediction from the perturbative QCD (PQCD) approach, $(0.20 \pm 0.04) \times \exp(-156^o i)$ [4,15]. The extracted P/T in Eq. (13) becomes smaller than $(0.77^{+0.58}_{-0.34}) \times \exp[(137^{+14}_{-21})^o i]$ from the old data [16,17], and closer to the PQCD prediction $(0.23^{+0.07}_{-0.05}) \times \exp[(143 \pm 5)^o i]$ [15,18]. The extracted P/T and T'/P' are consistent with those obtained in [9].

(ii) The recent $\pi\pi$, $K\pi$ data do not imply a large electroweak penguin amplitude, because of $|P^{(\prime)}_{ew}/P^{(\prime)}| \approx 0.2$, contrary to the conclusion in the literature [9,10,19–21]. The extracted $P^{(\prime)}_{ew}/P^{(\prime)}$, consistent with the standard-model estimation $(0.14^{+0.06}_{-0.05}) \exp[(3^{+23}_{-18})^o i]$ quoted in [9], shows no signal of new physics.

(iii) The recent data imply a large color-suppressed tree amplitude with $|C^{(\prime)}/T^{(\prime)}| \sim O(1)$ and with a constructive interference between $C^{(\prime)}$ and $T^{(\prime)}$. Our $C^{(\prime)}/T^{(\prime)}$ is in agreement with $1.22^{+0.25}_{-0.21} \times \exp[-(71^{+19}_{-25})^o i]$ derived in [9], but differs from that in [11] ([22]), which favors a larger (vanishing) relative strong phase between $C^{(\prime)}$ and $T^{(\prime)}$. Contrary to $P^{(\prime)}_{ew}/P^{(\prime)}$, the extracted $C^{(\prime)}/T^{(\prime)}$ is 4 times bigger than from the PQCD prediction. Note that $C^{(\prime)}$ represents an effective amplitude in the parametrization, which contains additional contributions compared to that calculated in PQCD.

(iv) The extracted weak phases $\phi_2 \sim 90^o$ and $\phi_3 \sim 60^o$ are consistent with those form the global unitarity triangle fit [23]. When the data of the mixing-induced CP asymmetry in the $B^0_d \to \pi^0\pi^0$ modes becomes available, ϕ_2 and ϕ_3 can be determined independently from the $B \to \pi\pi$, $K\pi$ decays, respectively, and the unitarity condition of the weak phases can be checked. The criteria in Eq. (7) will still apply to discriminate different solutions.

(v) The hierarchy in Eqs. (2) and (5) is not well respected by the extracted amplitude ratios. Nevertheless, these ratios arise from the central values of the data, and their ranges are expected to be as wide as found in [2]. More precise data are necessary for examining the power counting rules.

It should be stressed that the c-convention with the CKM matrix element product $V_t = V_{td}V^*_{tb}$ being eliminated has been adopted for the parametrization of the $B \to \pi\pi$ amplitudes in [9,16,17]. Therefore, their definitions of the ratios P/T and C/T differ from ours:

$$\begin{aligned} \frac{P}{T}\Big|_c &= \frac{(V_c/|V_t|)(P/T)|_t}{1 + (|V_u|/|V_t|)(P/T)|_t}, \\ \frac{C}{T}\Big|_c &= \frac{(C/T)|_t - (|V_u|/|V_t|)(P/T)|_t}{1 + (|V_u|/|V_t|)(P/T)|_t}, \end{aligned} \tag{17}$$

where the ratios P/T do not involve the weak phases, the subscript c (t) denotes the $c(t)$-convention, and the CKM matrix element product V_u is given by $V_u = V_{ud}V^*_{ub}$. Because of the large relative strong phase between P and T in Eq. (13), the magnitudes of the ratios in the c-convention are larger than those in the t-convention by $20\% \sim 30\%$, which does not affect the comparisons made above.

There are two reasons for the different conclusions drawn in this work and in [9,10,19]. First, if employing the SU(3) flavor symmetry as in the above references, i.e., substituting $C/T \approx 0.81e^{-58^o i}$ in Eq. (13) for C'/T' in Eq. (4), and solving for other amplitudes, we obtain $P'_{ew}/P' = 0.44e^{-79^o i}$, close to $0.36^{+0.52}_{-0.25}\exp[-(82^{+29}_{-36})^o]$ in [9]. It implies that the new physics signal may be a consequence of the exact SU(3) flavor symmetry, an assumption which is too strong as explained before [13]. Second, if adopting the old data [2] for those labeled by "updated", and solving Eq. (4), we derive

$$\frac{T'}{P'} = 0.26e^{-169^o i}, \quad \frac{P'_{ew}}{P'} = 0.41e^{-85^o i}, \\ \frac{C'}{T'} = 1.04e^{-51^o i}, \quad \phi_3 = 78^o, \tag{18}$$

in which P'_{ew}/P' is also close to that in [9]. It is then realized that the recent data have exhibited the tendency toward a small electroweak penguin amplitude. The SU(3) flavor symmetry was not fully relaxed in [10]: the strong phase of C/T remains equal for both the $\pi\pi$, $K\pi$ modes. The data adopted in [10] were not completely updated either, such as the $B^\pm \to K^0\pi^\pm$ branching ratio $(21.8 \pm 1.4) \times 10^{-6}$. Hence, it is not a surprise to conclude a large electroweak penguin amplitude.

Other observations from the updated data include: the $B^0_d \to K^\pm\pi^\mp$ modes involve only the penguin amplitude P' and the tree amplitude T'. Hence, the large CP asymmetry observed in these modes confirms the large relative strong phase between T' and P', as predicted by the PQCD approach [4]. The $B^\pm \to K^0\pi^\pm$ branching ratio has increased and become almost twice of the $B^0_d \to K^0\pi^0$ one, indicating that the magnitude of the electroweak penguin amplitude P'_{ew} needs not to be large as shown in Eq. (9). If the large relative phase between T' and P' is established, and P'_{ew} is small, the tiny CP asymmetry observed in the $B^\pm \to K^\pm\pi^0$ modes then implies an essential C' [24], whose effect is to orient $T' + C'$ along P' as shown in Eq. (9). A large P'_{ew} found in [9] is also a possible solution to the small CP asymmetry in the $B^\pm \to K^\pm\pi^0$ modes: the effect of P'_{ew} is to rotate P', such that it bisects the angle between $(T' + C')\exp(i\phi_3)$ and $(T' + C')\exp(-i\phi_3)$. This solution, corresponding to Eq. (11), however, has been ruled out as shown above. Similarly, the possible large CP asymmetry observed in the $B^0_d \to \pi^\pm\pi^\mp$ modes also hints a large relative strong phase between T and P. At last, we check the configuration between P_{ew} and $-(T + C)$, and find that their ratio, excluding the CKM matrix elements, is given by $0.024\exp(5^o i)$ from Eq. (13). This ratio, being only the central value, is roughly consistent with $0.013\exp(0^o i)$ from the isospin symmetry [25–27].

We have performed an $O(\lambda^2)$ analysis based on the topological-amplitude parametrizations for the $B \to \pi\pi$, $K\pi$ decays. Combining the recent $\pi\pi$, $K\pi$ data, such an investigation is allowed. We do not rely on the SU(3) flavor symmetry, but only require the extracted amplitude ratios from the $\pi\pi$, $K\pi$ modes to satisfy the approximate relations in Eq. (7). We have found that an exact solution from the $B \to \pi\pi$ data and an exact solution from the $B \to K\pi$ data, obeying this weaker and more reasonable requirement, indeed exist. These solutions show a large color-suppressed tree amplitude constructive to the tree amplitude, and a small electroweak penguin amplitude. The corresponding weak phases $\phi_2 \sim 90^o$ and $\phi_3 \sim 60^o$ should be convincing due to the consistency between the $\pi\pi$, $K\pi$ data. Compared to the predictions from the PQCD approach, the extracted P/T, T'/P', and $P^{(\prime)}_{ew}/P^{(\prime)}$ are all understandable. Only $C^{(\prime)}/T^{(\prime)}$, larger than the PQCD predictions, demands more study. This discrepancy may be attributed to the different definitions of $C^{(\prime)}$ in this work and in the PQCD approach. An explicit next-to-leading-order evaluation will answer whether this large ratio can be achieved. Because C' is important, the color-suppressed electroweak penguin amplitude $|P'^C_{ew}| \sim 0.22|C'| \sim 0.1|P'|$ [27] might cause some minor effect, which will be studied elsewhere. It has been also demonstrated that the recent data move toward a small electroweak penguin amplitude. Therefore, we intend to claim that there is no strong signal of new physics from the $B \to \pi\pi$, $K\pi$ decays. Our method provides a promising determination of the weak phases and of the topological amplitudes, whose ranges allowed by the data will be worked out in a forthcoming paper.

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