Puzzles in $B$ physics

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I discuss some puzzles observed in exclusive $B$ meson decays, concentrating on the large difference between the direct CP asymmetries in the $B^0 \to \pi^\mp K^\pm$ and $B^\pm \to \pi^0 K^\pm$ modes, the large $B^0 \to \pi^0 \pi^0$ branching ratio, and the large deviation of the mixing-induced CP asymmetries in the $b \to sq\bar{q}$ penguins from those in the $b \to c\bar{c}s$ trees.

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I. INTRODUCTION

The $B$ factories have accumulated enough events, which allow precision measurements of exclusive $B$ meson decays. These measurements sharpen the discrepancies between experimental data and theoretical predictions within the standard model, such that some puzzles have appeared. The recently observed direct CP asymmetries and branching ratios of the $B \to \pi K$, $\pi\pi$ decays \cite{1},

$$A_{CP}(B^0 \to \pi^\mp K^\pm) = (-10.8 \pm 1.7)\%,$$
$$A_{CP}(B^\pm \to \pi^0 K^\pm) = (4 \pm 4)\%,$$
$$B(B^0 \to \pi^\mp \pi^\pm) = (4.9 \pm 0.4) \times 10^{-6},$$
$$B(B^0 \to \pi^0 \pi^0) = (1.45 \pm 0.29) \times 10^{-6},$$

(1)

are prominent examples. The expected relations $A_{CP}(B^0 \to \pi^\mp K^\pm) \approx A_{CP}(B^\pm \to \pi^0 K^\pm)$ and $B(B^0 \to \pi^\mp \pi^\pm) \gg B(B^0 \to \pi^0 \pi^0)$ obviously contradict to the above data. The weak phase $\phi_1$, defined via the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{td} = |V_{td}| \exp(-i\phi_1)$ \cite{2}, can be extracted either from the tree-dominated or penguin-dominated modes. It has been estimated that the penguin pollution in the $b \to c\bar{c}s$ trees and the tree pollution in the $b \to sq\bar{q}$ penguins are about 5%. Therefore, it is expected that the measured mixing-induced CP asymmetries $S_{sq\bar{q}}$ are close to $S_{c\bar{c}s} = \sin(2\phi_1) \approx 0.685$ \cite{1}. However, a large deviation $\Delta S \equiv S_{sq\bar{q}} - S_{c\bar{c}s}$ has been measured.

In this talk I will review the recent studies of these subjects, concluding that the $B \to \pi K$ puzzle could be attributed to QCD uncertainty, the $B \to \pi\pi$ puzzle can not be resolved within the current theoretical development, and the $\Delta S$ puzzle might be a promising signal of new physics, if the data persist. I will not discuss another puzzle from the small longitudinal polarization fractions observed in the penguin-dominated $B \to VV$ decays, such as $B \to \phi K^*$ and $B \to \rho K^*$, since they involve different dynamics. A recent summary on this topic is referred to \cite{3}.

II. THE $B \to \pi K$ PUZZLE

To explain the $B \to \pi K$ puzzle, it is useful to adopt the topological-amplitude parametrization for two-body nonleptonic $B$ meson decays \cite{3}. The $B \to \pi K$ amplitudes are written, up to $O(\lambda^2)$, $\lambda \approx 0.22$ being the Wolfenstein parameter, as

$$A(B^+ \to \pi^+ K^0) = P^c,$$
$$\sqrt{2}A(B^+ \to \pi^0 K^+) = -P^c\left[1 + \frac{P^c}{P^c_i} + \left(\frac{T^c}{P^c_i} + \frac{C^c}{P^c_i}\right)e^{i\phi_3}\right],$$

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\[ A(B^0 \to \pi^- K^+) = -P' \left(1 + \frac{T'}{P} e^{i\phi_3} \right), \]
\[ \sqrt{2} A(B^0 \to \pi^0 K^0) = P' \left(1 - \frac{P'_{ew}}{P'} - \frac{C'}{P'} e^{i\phi_3} \right). \]

The notations \( T', C', P', \) and \( P'_{ew} \) stand for the color-allowed tree, color-suppressed tree, penguin, and electroweak penguin amplitudes, respectively, which obey the counting rules [3, 4].

\[ \frac{T'}{P'} \sim \lambda, \quad \frac{P'_{ew}}{P'} \sim \lambda, \quad \frac{C'}{P'} \sim \lambda^2. \]

The weak phase \( \phi_3 \) is defined via the CKM matrix element \( V_{ub} = |V_{ub}| \exp(-i\phi_3) \) [2]. The data \( A_{CP}(B^0 \to \pi^+ K^-) \approx -11\% \) indicate a sizable relative strong phase between \( T' \) and \( P' \), which verifies our prediction made years ago using the perturbative QCD (PQCD) approach [6]. Since both \( P'_{ew} \) and \( C' \) are subdominant, the approximate equality for the direct CP asymmetries \( A_{CP}(B^\pm \to \pi^0 K^\pm) \approx \frac{A_{CP}(B^0 \to \pi^+ K^-)}{2} \) is expected, which is, however, in conflict with the data in Eq. (1) dramatically.

It is then natural to conjecture a large \( P'_{ew} \) [8, 9, 10, 11, 12], which signals a new physics effect, a large \( C' \) [13, 14, 15, 16], which implies a missing mechanism in the standard model, or both [17, 18]. The large \( C' \) proposal seems to be favored by a recent analysis of the \( B \to \pi K, \pi \pi \) data based on the amplitude parametrization [13].

The PQCD predictions for the \( B \to \pi K, \pi \pi \) decays in \, [7, 11] are expected, and the \( C' \) are subdominant, the \( T' \) corrections increase \( C' \) by a factor of 3, and induce a large phase relative to \( T' \). This result can be understood from the value of the Wilson coefficient \( a_2(\mu) \) in Fig. 1, to which \( C' \) is proportional, at the characteristic scale \( \mu \approx \sqrt{m_b \Lambda} \approx 1.7 \) GeV, \( m_b \) being the \( B \) quark mass and \( \Lambda \) a hadronic scale. The larger \( C' \) renders the total tree amplitude \( T' + C' \) more or less parallel to the total penguin amplitude \( P' + P'_{ew} \) in the \( B^\pm \to \pi^0 K^\pm \) modes. Hence, it leads to nearly vanishing \( A_{CP}(B^\pm \to \pi^0 K^\pm) \) as shown in Table II and the \( B \to \pi K \) puzzle is resolved at the 1\( \sigma \) level. Our analysis also confirmed that the NLO corrections are under control in PQCD.

At last, we emphasize that the NLO PQCD predictions for the \( B^0 \to \pi^0 K^0 \) still fall short a bit compared to the data. It implies a new-physics phase associated with the electroweak penguin amplitude \( P'_{ew} \) [12, 21, 22, 23], such that it becomes orthogonal to the penguin amplitude \( P' \), and enhances the \( B^0 \to \pi^0 K^0 \) branching ratio. That is, we can not exclude the possibility of new physics effects in the \( B \to \pi K \) decays.
TABLE I: Branching ratios from PQCD in the NDR scheme in units of B

| Mode          | Data [1] | LO | LNLOWC | +VC | +QL | +MP | +NLO          |
|---------------|----------|----|--------|-----|-----|-----|---------------|
| B⁺ → π⁺K⁰⁺   | 24.1 ± 1.3 | 17.0 | 32.3 | 30.1 | 34.2 | 24.1 | 23.6 ± 14.5 (+13.8) |
| B⁻ → π⁻K⁻⁻   | 12.1 ± 0.8 | 10.2 | 18.4 | 17.1 | 19.4 | 14.0 | 13.6 ± 10.3 (+ 7.5) |
| B₀ → π₀K₀     | 18.9 ± 0.7 | 14.2 | 27.7 | 26.1 | 29.4 | 20.5 | 20.4 ± 16.1 (+11.5) |
| B₀ → π₀K₀     | 11.5 ± 1.0 | 5.7  | 12.1 | 11.4 | 12.8 | 8.7  | 8.7 ± 3.4 (+ 3.1)  |
| B₀ → π⁺π⁻     | 4.9 ± 0.4  | 7.0  | 6.8  | 6.6  | 6.9  | 6.7  | 6.5 ± 6.9 (+ 2.7)  |
| B⁺ → π⁺π⁻     | 5.5 ± 0.6  | 3.5  | 4.1  | 4.0  | 4.1  | 4.1  | 4.0 ± 3.4 (+ 1.7)  |
| B₀ → π⁺π⁻     | 1.45 ± 0.29 | 0.12 | 0.27 | 0.37 | 0.29 | 0.21 | 0.29 ± 0.50 (+0.13) |

TABLE II: Direct CP asymmetries from PQCD in the NDR scheme in percentage.

| Mode          | Data [1] | LO | LNLOWC | +VC | +QL | +MP | +NLO          |
|---------------|----------|----|--------|-----|-----|-----|---------------|
| B⁺ → π⁺K⁺     | -2 ± 4   | -1  | -1    | 0   | -1  | 0   | 0 ± 0 (±0)    |
| B⁻ → π⁻K⁻⁻    | 4 ± 4    | -8  | -6    | -2  | -5  | -8  | -1.6 ± 0.5 (+3) |
| B₀ → π⁺K⁺     | -10.8 ± 1.7 | -12 | -8    | -9  | -6  | -10 | -10.8 ± 4.5 (+5) |
| B₀ → π⁻K⁻⁻    | 2 ± 13   | -2  | 0     | -7  | 0   | 0   | -7.4 ± 0.3 (+2) |
| B₀ → π⁺π⁻     | 37 ± 10  | 14  | 19    | 21  | 16  | 20  | 18.1 ± 12 (+7) |
| B⁺ → π⁺π⁻⁻    | 1 ± 6    | 0   | 0     | 0   | 0   | 0   | 0 ± 0 (±0)    |
| B₀ → π⁺π⁻⁻    | 28 ± 40  | -4  | -34   | 65  | -41 | -43 | 63.3 ± 35 (+9) |

III. THE B → ππ PUZZLE

Similarly, the B → ππ decay amplitudes are parameterized as

\[ \sqrt{2}A(B^+ → π^+π^0) = -T \left[ 1 + \frac{C}{T} + \frac{P_{ew}}{T} e^{iφ_2} \right], \]

\[ A(B^0_d → π^+π^-) = -T \left[ 1 + \frac{P}{T} e^{iφ_2} \right], \]

\[ \sqrt{2}A(B^0_d → π^0π^0) = T \left[ \left( \frac{P}{T} - \frac{P_{ew}}{T} \right) e^{iφ_2} - \frac{C}{T} \right], \]

with the power counting rules,

\[ \frac{P}{T} \sim λ, \quad \frac{C}{T} \sim λ, \quad \frac{P_{ew}}{T} \sim λ^2. \]

The hierarchy of the branching ratios B(B⁰ → π⁰π⁰) ~ O(λ²)B(B⁰ → π⁺π⁻) is then expected. However, the data in Eq. 1 show B(B⁰ → π⁰π⁰) ~ O(λ)B(B⁰ → π⁺π⁻), giving rise to the B → ππ puzzle.

As indicated in Table II the NLO corrections, despite of increasing the color-suppressed tree amplitudes significantly, are not enough to enhance the B⁰ → π⁰π⁰ branching ratio to the measured value. A much larger amplitude ratio |C/T| ~ 0.8 must be obtained in order to resolve the puzzle. Nevertheless, the NLO corrections do improve the consistency of our predictions with the data: the predicted B⁰ → π⁺π⁻ (B⁰ → π⁰π⁰) branching ratio decreases (increases). To make sure the NLO effects observed in Sec. 2 are reasonable, we have applied the same PQCD formalism to the B → ρρ branching ratios, which are also sensitive to the color-suppressed tree contribution. It was found that the NLO PQCD predictions are in agreement with the data of the B⁰ → ρ⁺ρ⁻ and B⁺ → ρ⁰ρ⁰ branching ratios, and saturate the experimental upper bound of the B⁰ → ρ⁺ρ⁰ branching ratio as shown in Table III. We conclude that it is unlikely to accommodate the measured
$B^0 \to \pi^0 \pi^0$, $\rho^0 \rho^0$ branching ratios simultaneously in PQCD. Therefore, our resolution to the $B \to \pi K$ puzzle makes sense, and the $B \to \pi \pi$ puzzle is confirmed.

| Mode       | Data [1] | LO jet | LO jet SCET | +QL | +MP | +NLO |
|------------|----------|--------|-------------|-----|-----|------|
| $B^0 \to \rho^0 \rho^0$ | $25.2^{+14.0}_{-3.7}$ | 27.8   | 26.1        | 25.2 | 26.6 | 25.9 |
| $B^\pm \to \rho^\pm \rho^0$ | $19.1 \pm 3.5$ | 13.7   | 16.2        | 16.0 | 16.2 | 16.0 |
| $B^0 \to \rho^0 \rho^0$ | < 1.1    | 0.33   | 0.56        | 1.02 | 0.62 | 0.45 |

TABLE III: $B \to \rho \rho$ branching ratios from PQCD in the NDR scheme in units of $10^{-6}$.

It has been claimed that the $B \to \pi \pi$ puzzle is resolved in the QCD-improved factorization (QCDF) approach with an input from soft-collinear effective theory (SCET) [24]: the inclusion of the NLO jet function, the hard coefficient of SCET, into the QCDF formula for the color-suppressed tree amplitude gives sufficient enhancement of the $B^0 \to \pi^0 \pi^0$ branching ratio. It is certainly necessary to investigate whether the new mechanism proposed above deteriorates the consistency of theoretical results with other data. Therefore, we have extended the formalism in [24] to the $B \to \rho \rho$ decays as a check [26]. Because of the end-point singularities present in twist-3 spectator amplitudes and in annihilation amplitudes, these contributions have to be parameterized in QCDF [24]. Different scenarios for choosing the free parameters, labelled by “default”, “S1”, “S2”, ..., and “S4”, have been proposed in [27]. As shown in Table IV, the large measured $B^0 \to \pi^0 \pi^0$ branching ratio can be accommodated by including the NLO jet function, when the parameter scenario S4 is adopted. However, this effect overshoots the upper bound of the $B^0 \to \rho^0 \rho^0$ branching ratio very much. We have surveyed the other scenarios, and found the results from S1 and S3 (S2) similar to those from the default (S4). That is, it is also unlikely to accommodate the $B \to \pi \pi$, $\rho \rho$ data simultaneously in QCDF.

| Mode       | Data [1] | default, LO jet | default, LO jet | S4, LO jet | S4, LO jet | S4, NLO jet |
|------------|----------|-----------------|-----------------|------------|------------|-------------|
| $B^\pm \to \pi^\pm \pi^0$ | $5.5 \pm 0.6$ | 6.02          | 6.24          | 5.07       | 5.77       |
| $B^0 \to \pi^0 \pi^\pm$ | $4.9 \pm 0.4$ | 8.90          | 8.69          | 5.22       | 4.68       |
| $B^0 \to \pi^0 \pi^0$ | $1.45 \pm 0.29$ | 0.36         | 0.40          | 0.72       | 1.07       |
| $B^\pm \to \rho^\pm \rho^0_L$ | $19.1 \pm 3.5$ | 18.51        | 19.48         | 16.61      | 18.64      |
| $B^0 \to \rho^0 \rho^0_L$ | $25.2^{+3.6}_{-3.7}$ | 25.36        | 24.42         | 18.48      | 16.76      |
| $B^0 \to \rho^0 \rho^0_L$ | < 1.1    | 0.43          | 0.66          | 0.92       | 1.73       |

TABLE IV: Branching ratios from QCDF with the input of the SCET jet function in units of $10^{-6}$. The data for the $B \to \rho \rho$ decays include all polarizations.

There exists an alternative phenomenological application of SCET [28, 29], where the jet function, characterized by the scale of $O(\sqrt{m_b})$, is regarded as being incalculable. Its contribution, together with other nonperturbative parameters, such as the charming penguin, were then determined by the $B \to \pi \pi$ data. That is, the color-suppressed tree amplitude can not be explained, but the data are used to fit for the phenomenological parameters in the theory. Predictions for the $B \to \pi \pi$, $KK$ decays were then made based on the obtained parameters and partial SU(3) flavor symmetry [29]. Final-state interaction (FSI) is certainly a plausible resolution to the $B \to \pi \pi$ puzzle, but the estimate of its effect is quite model-dependent. Even opposite conclusions were drawn sometimes. When including FSI either into naive factorization [30] or into QCDF [31], the $B^0 \to \pi^0 \pi^0$ branching ratio was treated as an input in order to fix the involved free parameters. Hence, no resolution was really proposed. It has been found that FSI, evaluated in the Regge model, is insufficient to account for the observed $B^0 \to \pi^0 \pi^0$ branching ratio [32].

IV. THE $\Delta S$ PUZZLE

The time-dependent CP asymmetry of the $B^0 \to \pi^0 K_S$ mode is defined as

$$A_{CP}(B^0(t) \to \pi^0 K_S) = \frac{B(B^0(t) \to \pi^0 K_S) - B(B^0(t) \to \pi^0 K_S)}{B(B^0(t) \to \pi^0 K_S) + B(B^0(t) \to \pi^0 K_S)}$$
\[ A_{\pi^0 K_S} = A_{\pi^0 K_S} \cos(\Delta M_d t) + S_{\pi^0 K_S} \sin(\Delta M_d t) , \]

with the mass difference \( \Delta M_d \) of the two \( B \)-meson mass eigenstates, and the direct asymmetry and the mixing-induced asymmetry,

\[ A_{\pi^0 K_S} = \frac{|\lambda_{\pi^0 K_S}|^2 - 1}{1 + |\lambda_{\pi^0 K_S}|^2}, \quad S_{\pi^0 K_S} = \frac{2 \text{Im}(\lambda_{\pi^0 K_S})}{1 + |\lambda_{\pi^0 K_S}|^2}, \]

respectively. The \( B^0 \to \pi^0 K_S \) decay has a CP-odd final state, and the corresponding factor,

\[ \lambda_{\pi^0 K_S} = -e^{-2i\phi_1} \frac{P' - P'_{ew} - C' e^{-i\delta_3}}{P' - P'_{ew} - C' e^{i\delta_3}}. \]

After obtaining the values of the various topological amplitudes, we computed the mixing-induced CP asymmetries through Eq. (10). Since \( C' \) is of \( O(\lambda^2) \) compared to \( P' \), it is expected that the LO PQCD result of \( S_{\pi^0 K_S} \approx 0.70 \) is close to \( S_{\pi^0 K_S} \approx 0.685 \) as shown in Table V. It is known that the leading deviation of \( \Delta S_{\pi^0 K_S} \) is of \( O(\lambda^2) \) compared to \( P' \), and \( \Delta S_{\pi^0 K_S} \) does not increase much in NLO PQCD. This tendency persists in other \( b \to s q \bar{q} \) penguin decays. The mixing-induced CP asymmetry in the \( B^0 \to \pi^+ \pi^- \) can be defined in a similar way. However, the penguin pollution \( P \) is of \( O(\lambda) \) relative to \( T \) in these decays, such that a larger deviation of \( S_{\pi^0 K_S} \) from \( S_{\pi^0 K_S} \) was found. The PQCD results of \( S_{\pi^0 K_S} \) are consistent with the data, but those of \( S_{\pi^0 K_S} \) are not. Moreover, PQCD predicts \( \Delta S_{\pi^0 K_S} > 0 \), opposite to the measured value. This result is in agreement with those derived in the literature. Hence, it is not easy to explain the data of \( S_{\pi^0 K_S} \).

|          | Data | LO | LO_{NLOWC} | +VC | +QL | +MP | +NLO |
|----------|------|----|-------------|-----|-----|-----|------|
| \( S_{\pi^0 K_S} \) | 0.31 ± 0.26 | 0.70 | 0.73 | 0.74 | 0.73 | 0.73 | 0.74±0.02 (+0.01) |
| \( S_{\pi^0} \)    | -0.50 ± 0.12 | -0.34 | -0.49 | -0.47 | -0.51 | -0.41 | -0.42±0.00 (+0.05) |

TABLE V: Mixing-induced CP asymmetries from PQCD in the NDR scheme.

V. CONCLUSION

Many puzzles in exclusive \( B \) meson decays have been observed recently. The data \( A_{CP} (B^{\pm} \to \pi^0 K^{\pm}) \) much different from \( A_{CP} (B^0 \to \pi^0 K^0) \) could be resolved in NLO PQCD by taking into account the vertex corrections. We found that there is no satisfactory resolution to the \( B \to \pi \pi \) puzzle in the literature: the available proposals are either data fitting, or can not survive the constraints from the \( B \to \rho \rho \) data under the current theoretical development. The NLO effects push the deviation \( \Delta S_{\pi^0 K_S} \) toward the even larger positive value. Therefore, the measurement of the mixing-induced CP asymmetries in the penguin-dominated modes provides an opportunity of discovering new physics.

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