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Some Puzzles in B Physics*

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Abstract I discuss some puzzles observed in exclusive B meson decays: the large difference between the direct CP asymmetries of the $B^0 \to \pi^{\mp}K^{\pm}$ and $B^{\pm} \to \pi^0 K^{\pm}$ modes, and the small longitudinal polarization fraction of the $B \to \phi K^*$ modes. These puzzles, being attributed to QCD uncertainty, may not be regarded as signals of new physics.

Key words B physics, perturbative QCD, polarization fraction

1 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 of the $B \to \pi K$ decays[1],

$$\begin{aligned} A_{\mathrm{CP}}(B^0 \to \pi^{\mp}K^{\pm}) &= (-11.5 \pm 1.8)\%\,, \\ A_{\mathrm{CP}}(B^{\pm} \to \pi^0 K^{\pm}) &= (4 \pm 4)\%\,, \end{aligned} \tag{1}$$

are a prominent example. The expected relation $A_{\mathrm{CP}}(B^0 \to \pi^{\mp}K^{\pm}) \approx A_{\mathrm{CP}}(B^{\pm} \to \pi^0 K^{\pm})$ obviously contradicts to the above data. The polarizations of the $B \to \phi K^*$ decays are another puzzle. The polarization fractions of the tree-dominated B meson decays, such as $B^0 \to (D_s^{*+}, D^{*+}, \rho^+)D^{*-}$, can be understood by kinematics in the heavy-quark limit. Those of the $B \to (\rho, \omega)\rho$ modes are understood by kinematics in the large-energy limit. For penguin-dominated modes, such as those listed in Table 1, the polarization fractions deviate from the naive counting rules based on kinematics[2]: the annihilation contribution from the $(S-P)(S+P)$ operators and the nonfactorizable contribution decrease R_{L} to about 0.75 for the pure-penguin $B^+ \to \rho^+ K^{*0}$ decay. The puzzling $B \to \phi K^*$ decays are also pure-penguin, but theirs $R_{\mathrm{L}} \sim 0.5$ shown in Table 1 are much lower than 0.75.

Table 1. Polarization fractions in the penguin-dominated $B \to VV$ decays.

mode	Pol. fraction	Belle	Babar
$B^+ \to \phi K^{*+}$	R_{L}	$0.49 \pm 0.13 \pm 0.05$[3]	$0.46 \pm 0.12 \pm 0.03$[4]
	$R_{\perp}$	$0.12^{+0.11}_{-0.08} \pm 0.03$[3]	
$B^0 \to \phi K^{*0}$	R_{L}	$0.52 \pm 0.07 \pm 0.05$[3]	$0.52 \pm 0.05 \pm 0.02$[5]
	$R_{\perp}$	$0.30 \pm 0.07 \pm 0.03$[3]	$0.22 \pm 0.05 \pm 0.02$[5]
mode	Pol. fraction	Belle	Babar
$B^+ \to \rho^0 K^{*+}$	R_{L}		$0.96^{+0.04}_{-0.15} \pm 0.04$[4]
$B^+ \to \rho^+ K^{*0}$	R_{L}	$0.50 \pm 0.19^{+0.05}_{-0.07}$[6]	$0.79 \pm 0.08 \pm 0.04 \pm 0.02$[7]

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These puzzles have been claimed to be signals of physics beyond the standard model. In this talk I will explain that they could be simply attributed to QCD uncertainty.

2 The $\mathrm{B}\to\pi\mathrm{K}$ puzzle

To explain the $\mathrm{B}\to\pi\mathrm{K}$ puzzle, it is useful to adopt the topological-amplitude parametrization[8] for these decays. The $\mathrm{B}\to\pi\mathrm{K}$ decay amplitudes are written, up to $O(\lambda^2)$, $\lambda\approx 0.22$ being the Wolfenstein parameter, as

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

where the notations T', C', P', and P'_{ew} stand for the color-allowed tree, color-suppressed tree, penguin, and electroweak penguin amplitudes, respectively, and the weak phase ϕ_3 is defined via the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{\mathrm{ub}}=|V_{\mathrm{ub}}|\exp(-\mathrm{i}\phi_3)$[9]. These amplitudes obey the counting rules[10, 11],

$$\frac{T'}{P'}\sim\lambda\,,\quad \frac{P'_{\mathrm{ew}}}{P'}\sim\lambda\,,\quad \frac{C'}{P'}\sim\lambda^2\,. \qquad(3)$$

The data $A_{\mathrm{CP}}(\mathrm{B}^0\to\pi^\mp\mathrm{K}^\pm)\approx -11\%$ implies a sizable relative strong phase between T' and P', which verifies our prediction made years ago using the PQCD approach[12]. Since both P'_{ew} and C' are subdominant, the approximate equality for the direct CP asymmetries $A_{\mathrm{CP}}(\mathrm{B}^\pm\to\pi^0\mathrm{K}^\pm)\approx A_{\mathrm{CP}}(\mathrm{B}^0\to\pi^\mp\mathrm{K}^\pm)$ is expected, which is, however, in conflict with the data in Eq. (1) dramatically.

It is then natural to conjecture a large P'_{ew}[13—17], which signals a new physics effect, a large C'[18—21], which implies a missing mechanism in the standard model, or both[22, 23]. The large C' proposal seems to be favored by a recent analysis of the $\mathrm{B}\to\pi\mathrm{K}$, $\pi\pi$ data based on the amplitude parameterization[18]. Note that the current perturbative QCD (PQCD) predictions for the two-body nonleptonic B decays were derived from the leading-order (LO) and leading-power formalism. While LO PQCD indicates a negligible C', it is possible that this supposedly tiny amplitude receives a significant subleading correction. Hence, before claiming a new physics signal, one should at least examine whether the next-to-leading-order (NLO) effects could enhance C' sufficiently.

In Ref. [24] we have calculated the important NLO contributions to the $\mathrm{B}\to\pi\mathrm{K}$, $\pi\pi$ decays from the vertex corrections, the quark loops, and the magnetic penguins. The higher-power corrections have not yet been under good control, and were not considered. We found that the corrections from the quark loops and from the magnetic penguins, being about 10% of the LO penguin amplitude, decrease only the $\mathrm{B}\to\pi\mathrm{K}$ branching ratios as indicated in Table 2. The vertex corrections tend to increase C' by a factor of 3. This larger C' leads to nearly vanishing $A_{\mathrm{CP}}(\mathrm{B}^\pm\to\pi^0\mathrm{K}^\pm)$ without changing the branching ratios, which are governed by P'. The $\mathrm{B}\to\pi\mathrm{K}$ puzzle is then resolved as shown in Table 3. Our analysis has also confirmed that the NLO corrections are under control in PQCD.

Table 2. Branching ratios in the NDR scheme ($\times 10^{-6}$). The label $\mathrm{LO_{NLOWC}}$ means the LO results with the NLO Wilson coefficients, and +VC, +QL, +MP, and +NLO mean the inclusions of the vertex corrections, of the quark loops, of the magnetic penguin, and of all the above NLO corrections, respectively.

mode	data[1]	LO	$\mathrm{LO_{NLOWC}}$	+VC	+QL	+MP	+NLO
$\mathrm{B}^\pm\to\pi^\pm\mathrm{K}^0$	24.1 ± 1.3	17.3	32.9	31.6	34.9	24.5	$24.9^{+13.9}_{-\ 8.2}$
$\mathrm{B}^\pm\to\pi^0\mathrm{K}^\pm$	12.1 ± 0.8	10.4	18.7	17.7	19.7	14.2	$14.2^{+10.2}_{-\ 5.8}$
$\mathrm{B}^0\to\pi^\mp\mathrm{K}^\pm$	18.9 ± 0.7	14.3	28.0	26.9	29.7	20.7	$21.1^{+15.7}_{-\ 8.4}$
$\mathrm{B}^0\to\pi^0\mathrm{K}^0$	11.5 ± 1.0	5.7	12.2	11.9	13.0	8.8	$9.2^{+\ 5.6}_{-\ 3.3}$
$\mathrm{B}^0\to\pi^\mp\pi^\pm$	5.0 ± 0.4	7.1	6.8	6.6	6.9	6.7	$6.6^{+\ 6.7}_{-\ 3.8}$
$\mathrm{B}^\pm\to\pi^\pm\pi^0$	5.5 ± 0.6	3.5	4.2	4.1	4.2	4.2	$4.1^{+\ 3.5}_{-\ 2.0}$
$\mathrm{B}^0\to\pi^0\pi^0$	1.45 ± 0.29	0.12	0.28	0.37	0.29	0.21	$0.30^{+0.49}_{-0.21}$

Table 3. Direct CP asymmetries in the NDR scheme.

mode	data[1]	LO	LO$_{\rm NLOWC}$	+VC	+QL	+MP	+NLO
$\rm B^{\pm}\to\pi^{\pm}K^0$	-0.02 ± 0.04	-0.01	-0.01	-0.01	0.00	-0.01	0.00 ± 0.00
$\rm B^{\pm}\to\pi^0K^{\pm}$	0.04 ± 0.04	-0.08	-0.06	-0.01	-0.05	-0.08	$-0.01^{+0.03}_{-0.05}$
$\rm B^0\to\pi^{\mp}K^{\pm}$	-0.115 ± 0.018	-0.12	-0.08	-0.09	-0.06	-0.10	$-0.09^{+0.06}_{-0.08}$
$\rm B^0\to\pi^0K^0$	—	-0.02	0.00	-0.07	0.00	0.00	$-0.07^{+0.03}_{-0.03}$
$\rm B^0\to\pi^{\mp}\pi^{\pm}$	0.37 ± 0.10	0.14	0.19	0.21	0.16	0.20	$0.18^{+0.20}_{-0.12}$
$\rm B^{\pm}\to\pi^{\pm}\pi^0$	0.01 ± 0.06	0.00	0.00	0.00	0.00	0.00	0.00 ± 0.00
$\rm B^0\to\pi^0\pi^0$	$0.28^{+0.40}_{-0.39}$	-0.04	-0.34	0.65	-0.41	-0.43	$0.63^{+0.35}_{-0.34}$

The NLO corrections, though increasing the color-suppressed tree amplitudes significantly, are not enough to enhance the $\rm B^0\to\pi^0\pi^0$ branching ratio to the measured value. A much larger amplitude ratio $|C/T|\sim0.8$ must be obtained in order to resolve this puzzle[18]. Nevertheless, the NLO corrections do improve the consistency of our predictions with the data: the predicted $\rm B^0\to\pi^{\pm}\pi^{\mp}$ ($\rm B^0\to\pi^0\pi^0$) branching ratio decreases (increases). Viewing the consistency of the PQCD predictions with the tiny measured $\rm B^0\to K^0\overline{K}^0$ and $\rm B^0\to\rho^0\rho^0$ branching ratios, we think that our NLO results for the $\rm B\to\pi\pi$ decays are reasonable. In soft-collinear effective theory (SCET)[25], the large $|C/T|$ comes from a fit to the data, instead of from an explicit evaluation of the amplitudes. Hence, the $\rm B\to\pi\pi$ puzzle remains.

3 The $\rm B\to\phi K^*$ puzzle

Many attempts to resolve the $\rm B\to\phi K^*$ polarizations have been proposed, which include new physics[26, 27], the annihilation contribution[28] in the framework of QCD-improved factorization (QCDF)[29], the charming penguin in SCET[25], the rescattering effect[30—32], and the b → sg transition (the magnetic penguin)[33]. We have carefully analyzed these proposals[34], and found that none of them is satisfactory.

These decays have been studied in the PQCD approach[12, 35, 36], and the results of the branching ratios, the magnitudes of the helicity amplitudes $A_{\rm L}$, $A_{\parallel}$, and $A_{\perp}$, and their relative strong phases $\phi_{\parallel}$ and $\phi_{\perp}$ are summarized in Table 4[2]. The normalization of these amplitudes have been chosen, such that they satisfy $|A_{\rm L}|^2+|A_{\parallel}|^2+|A_{\perp}|^2=1$, with $|A_{\rm L}|^2=R_{\rm L}$, $|A_{\parallel}|^2=R_{\parallel}$, and $|A_{\perp}|^2=R_{\perp}$. The first rows (I), coming only from the factorizable emission topology, correspond to the results under the factorization assumption (FA)[37]. It is obvious that the polarization fractions $R_{\rm L}\approx0.92$ and $R_{\parallel}\approx R_{\perp}\approx0.04$ follow the naive counting rules $R_{\rm L}\sim1-O(m_{\phi}^2/m_{\rm B}^2)$, $R_{\parallel}\sim R_{\perp}\sim O(m_{\phi}^2/m_{\rm B}^2)$, $m_{\rm B}$ (m_{ϕ}) being the B(ϕ) meson mass. The next-to-leading-power annihilation amplitudes, mainly from the $(S-P)(S+P)$ operators, and the nonfactorizable amplitudes bring the first rows into the fourth ones (IV) with the fractions $R_{\rm L}\approx0.75$. It is easy to understand the sizable deviation from the naive counting rules caused by these subleading corrections, which are of $O(m_{\phi}/m_{\rm B})$ for all the three final helicity states[2]. However, the total effect, as shown in Table 4, is not sufficient to lower $R_{\rm L}$ of the $\rm B\to\phi K^*$ decays down to around 0.5.

Tabel 4. (Ⅰ) Without the nonfactorizable and annihilation contributions, (Ⅱ) add only the nonfactorizable contribution, (Ⅲ) add only the annihilation contribution, and (Ⅳ) add both the nonfactorizable and annihilation contributions. The last row is for $A_0=0.28$.

mode	$Br(10^{-6})$	$\lvert A_{\rm L}\rvert^2$	$\lvert A_{\parallel}\rvert^2$	$\lvert A_{\perp}\rvert^2$	$\phi_{\parallel}$/rad	$\phi_{\perp}$/rad
$\rm \phi K^{*0}$(Ⅰ)	14.48	0.923	0.040	0.035	π	π
(Ⅱ)	13.25	0.860	0.072	0.063	3.30	3.33
(Ⅲ)	16.80	0.833	0.089	0.078	2.37	2.34
(Ⅳ)	14.86	0.750	0.135	0.115	2.55	2.54
$\rm \phi K^{*+}$(Ⅰ)	15.45	0.923	0.040	0.035	π	π
(Ⅱ)	14.17	0.860	0.072	0.063	3.30	3.33
(Ⅲ)	17.98	0.830	0.094	0.075	2.37	2.34
(Ⅳ)	15.96	0.748	0.133	0.111	2.55	2.54
$\rm \phi K^{*0}$	$10.2^{+2.5}_{-2.1}$	$0.59^{+0.02}_{-0.02}$	$0.22^{-0.01}_{+0.01}$	$0.19^{-0.01}_{+0.01}$	$2.32^{+0.11}_{-0.13}$	$2.31^{+0.12}_{-0.13}$

As emphasized above, the $\mathrm{B}\to\phi\mathrm{K}^*$ polarizations are very unique, and it is difficult to find new mechanism, which affects only these modes but not others. To explain our idea, we quote the explicit expressions of the three helicity amplitudes in terms of the $\mathrm{B}\to\mathrm{K}^*$ transition form factors in FA[34],

$$A_{\mathrm{L}} \propto 2r_2\epsilon_2^*(L)\cdot\epsilon_3^*(L)A_0\,, \tag{4}$$

$$A_{\parallel} \propto -\sqrt{2}(1+r_2)A_1\,, \tag{5}$$

$$A_{\perp} \propto -\frac{2r_2r_3}{1+r_2}\sqrt{2[(v_2\cdot v_3)^2-1]}V\,, \tag{6}$$

with the K^* (ϕ) meson velocity v_2 (v_3) and polarization vector ϵ_2 (ϵ_3), $r_2=m_{\mathrm{K}^*}/m_{\mathrm{B}}$ and $r_3=m_\phi/m_{\mathrm{B}}$. The form factors A_0, A_1, and V in the standard definitions obey the symmetry relations in the large-energy limit [38, 39],

$$\frac{m_{\mathrm{B}}}{m_{\mathrm{B}}+m_{\mathrm{K}^*}}V=\frac{m_{\mathrm{B}}+m_{\mathrm{K}^*}}{2E}A_1=T_1=\frac{m_{\mathrm{B}}}{2E}T_2\,, \tag{7}$$

$$\frac{m_{\mathrm{K}^*}}{E}A_0=\frac{m_{\mathrm{B}}+m_{\mathrm{K}^*}}{2E}A_1-\frac{m_{\mathrm{B}}-m_{\mathrm{K}^*}}{m_B}A_2\,, \tag{8}$$

where T_1 and T_2 are the form factors involved in the $\mathrm{B}\to\mathrm{K}^*\gamma$ decays, and E is the K^* meson energy.

The results in Table 4 correspond to the form factors $A_0=0.40$, $A_1=0.26$ and $V=0.35$. First, the $\mathrm{B}\to\mathrm{K}^*\gamma$ branching ratios have constrained the form factors $T_1\approx T_2\approx 0.3$[40, 41], which are also in agreement with the lattice result[42]. Compared to the symmetry relation in Eq. (7), it is obvious that PQCD has given reasonable values of A_1 and V. Second, there has not yet been any measurement, except $\mathrm{B}\to\phi\mathrm{K}^*$, which constrains A_0. The other penguin-dominated $\mathrm{B}\to\rho(\omega)\mathrm{K}^*$ decays are mainly governed by the $\mathrm{B}\to\rho(\omega)$ form factors. Third, the PQCD predictions for the $\mathrm{B}\to\phi\mathrm{K}^*$ branching ratios in Table 4 are larger than the data[1],

$$\begin{aligned} B(\mathrm{B}^0\to\phi\mathrm{K}^{*0}) &= (9.5\pm0.9)\times10^{-6}\,,\\ B(\mathrm{B}^+\to\phi\mathrm{K}^{*+}) &= (9.7\pm1.5)\times10^{-6}\,. \end{aligned} \tag{9}$$

The above three observations hint that the PQCD results for the transverse components of the $\mathrm{B}\to\phi\mathrm{K}^*$ decays should have been reasonable, and that the longitudinal components may have been overestimated. We are then led to conjecture that a smaller A_0 will resolve the puzzle, giving both lower R_{L} and lower branching ratios.

We then choose the asymptotic models for the K^* meson distribution amplitudes relevant to the evaluation of A_0:

$$\begin{aligned} \phi_{\mathrm{K}^*}(x) &= \frac{3f_{\mathrm{K}^*}}{\sqrt{2N_{\mathrm{c}}}}x(1-x)\,,\\ \phi_{\mathrm{K}^*}^t(x) &= \frac{f_{\mathrm{K}^*}^{\mathrm{T}}}{2\sqrt{2N_{\mathrm{c}}}}3(1-2x)^2\,,\\ \phi_{\mathrm{K}^*}^{\mathrm{s}}(x) &= \frac{f_{\mathrm{K}^*}^{\mathrm{T}}}{2\sqrt{2N_{\mathrm{c}}}}3(1-2x)\,, \end{aligned} \tag{10}$$

which lead to $A_0=0.28$, about 70% of the original value. The model-dependent evaluations of A_0 vary in a wide range from 0.31 to 0.47, and $A_0\approx0.3$ has been supported by the recent covariant light-front QCD (LFQCD) calculation[43]. The models for the distribution amplitudes $\phi_{\mathrm{K}^*}^{\mathrm{T}}$, $\phi_{\mathrm{K}^*}^{\mathrm{v}}$ and $\phi_{\mathrm{K}^*}^{\mathrm{a}}$, relevant to the evaluation of the form factors A_1 and V, and those for the ϕ meson distribution amplitudes and for the B meson wave function, remain the same as in Ref. [2]. The resultant numerical outcomes are listed as the last row in Table 4, which are consistent with the $\mathrm{B}^0\to\phi\mathrm{K}^{*0}$ data.

4 Conclusion

Many puzzles in exclusive B meson decays have been observed recently. The data $A_{\mathrm{CP}}(\mathrm{B}^\pm\to\pi^0\mathrm{K}^\pm)$ much different from $A_{\mathrm{CP}}(\mathrm{B}^0\to\pi^\mp\mathrm{K}^\pm)$ are not expected by the naive power counting rules for the topological amplitudes. Is the difference due to a new-physics effect in the electroweak penguin amplitude, or simply to a larger color-suppressed tree amplitude? The very tiny longitudinal polarization fraction measured in the $\mathrm{B}\to\phi\mathrm{K}^*$ decays is not consistent with the naive counting rules based on kinematics. Are these data due to new physics effect, or to QCD uncertainty from the unknown $\mathrm{B}\to\mathrm{K}^*$ form factor A_0? New physics may be right at the corner, but we have to examine QCD effects carefully.

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B物理中的难题*

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摘要 讨论单举B介子衰变中的难题, 包括直接CP非对称性及纵向极化分支比, 这些难题可能皆归因于量子色动力学的不准确度, 并非新物理的讯号.

关键词 B物理 微扰量子色动力学 极化分支比

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