Systematic Investigation of Possibilities for New Physics Effects in $b \rightarrow s$ Penguin Processes

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Although recent experimental results in $b \rightarrow s$ penguin process seem to be roughly consistent with the standard model predictions, there may be still large possibilities of new physics hiding in this processes. Therefore, here we investigate systematically the potential new physics effects that may appear in time-dependent CP asymmetries of $B \rightarrow \phi K^0$, $B \rightarrow \eta' K^0$ and $B \rightarrow K^0 \pi^0$ decay modes, by classifying the cases for the values of the mixing-induced indirect CP asymmetries, $S_{\phi K^0}$, $S_{\eta' K^0}$, $S_{K^0 \pi^0}$ which are compared to $S_{J/\psi K^0}$. We also show that several $B_s$ decay modes may help to resolve the ambiguities in such an analysis. Through combining analysis with the time-dependent CP asymmetries of $B_s$ decay modes such as $B_s \rightarrow \phi \eta'$, $B_s \rightarrow \eta' \pi^0$ and $B_s \rightarrow K^0 \eta'$, we can determine where the new CP phases precisely come from.

§1. Introduction

According to the experimental results from Belle$^1$ and BaBar$^2$ collaborations which were presented before the Lepton-Photon Conference 2005 (LP05), there appeared to be a large discrepancy between the time-dependent CP asymmetries extracted from $B \rightarrow J/\psi K$ and those from $b \rightarrow s$ penguin processes. Based on the standard model (SM) predictions, where no significant differences are expected among those processes, this apparent experimental discrepancy may provide an evidence of new physics (NP) effect in the CP asymmetries beyond what is understood by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism$^3$. Hence many scenarios of new physics have been investigated by many authors$^3$. With the newest results$^5$ reported at LP05, the discrepancy is substantially reduced, and the CP asymmetries of $B \rightarrow \phi K$ mode seem to be almost consistent with the SM predictions. However, it does not mean that the possibility of NP has completely disappeared at all. According to the results for the other $b \rightarrow s$ penguin processes, there still remain some hints of discrepancies. Therefore, we investigate more carefully to find the NP effects hiding in the $B$ decays.

The time-dependent CP asymmetry is defined as follows$^3$

$$\frac{\Gamma(B_{phys}^0(t) \rightarrow f_{CP}) - \Gamma(B_{phys}^0(t) \rightarrow \bar{f}_{CP})}{\Gamma(B_{phys}^0(t) \rightarrow f_{CP}) + \Gamma(B_{phys}^0(t) \rightarrow \bar{f}_{CP})} = A_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

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Here \( A_f \) indicates the direct CP violation in the decay \( B^0 \rightarrow f_{CP} \), and \( S_f \) describes a \textit{mixing-induced} indirect CP violation due to the interference between \( B^0 \rightarrow B_s^0 \) mixing and its decay process. And \( \phi_M \) represents a weak phase in the \( B^0 \rightarrow B_s^0 \) mixing. Within the SM the mixing phase \( \phi_M \) is just a CKM phase \( \phi_1 \) for \( B_s^0 \) system, whereas it is almost zero\(^3\) for \( B^0 \) system. If there is no direct CP asymmetry and only the SM phase exists in the \( B^0 \rightarrow B_s^0 \) mixing, then the mixing induced indirect CP asymmetry, with \( A_f = 0 \), becomes

\[
S_f = \left\{ \begin{array}{ll}
sin(2\phi_1 + 2\phi_D) & \text{for } B^0_d \text{ system,} \\
\sin(2\phi_D) & \text{for } B^0_s \text{ system,}
\end{array} \right.
\]

(1.4)

where \( \phi_D \) is a weak phase in the decay amplitude defined by \( 2\phi_D = \text{Arg} \frac{A(B^0 \rightarrow f_{CP})}{A(B^0 \rightarrow f_{CP})} \).

In Table 1 we list recent experimental results\(^5\) of the time-dependent CP asymmetries for several relevant modes. It appears that for the indirect CP asymmetry, \( S_f \), there are apparent differences between \( B \rightarrow J/\psi K \) mode and other \( b \rightarrow s \) penguin-dominated modes such as \( B \rightarrow \eta' K^0 \), at a level of two standard deviations. On the other hand, the direct CP asymmetries are consistent with zero in all cases.

Motivated by those experimental results, here we investigate possible NP effects in \( b \rightarrow s \) penguin processes, in particular, \( B \rightarrow \phi K, B \rightarrow \eta' K \) and \( B \rightarrow K^0_\pi^0 \), which are relatively easy to be compared with many measurable processes diagrammatically. Using the topological quark diagrammatic decomposition method,\(^11\) the amplitudes of the modes can be expressed\(^**\) as follows:

\[
A(B \rightarrow \phi K) = (\hat{P}_s^s + \hat{S}_s^s - \frac{1}{3} \hat{P}_{EW}^s)V_{tb}^* V_{ts},
\]

(1.5)

\(^*\) We neglect the tiny weak phase existing in \( B_s - B_s \) system. In more accurate analysis the effects may need to consider carefully, but this paper is not still in such situation.

\(^**\) More complete and useful expansion for all charmless \( B \) decay modes including higher order contributions has been shown in, for example, Ref.\(^12\). Here, for simplicity, we use the most simple grammatical decomposition based on Ref.\(^10\).

| \( f \)       | \( A_f \)          | \( S_f \)          | \( \text{Br}(B \rightarrow f) \times 10^6 \) |
|-------------|-------------------|-------------------|------------------------------------------|
| \( J/\psi K^0 \) | -0.027±0.028     | 0.685±0.032      | 850±50                                   |
| \( \phi K^0 \) | 0.09±0.14         | 0.47±0.19        | 8.3±1.2                                  |
| \( \eta' K^0 \) | 0.07±0.07         | 0.50±0.09        | 68.6±4.2                                 |
| \( K^0_\pi^0 \) | 0.02±0.13         | 0.31±0.26        | 11.5±1.0                                 |

Table 1. The experimental results of direct \((A_f)\) and indirect \((S_f)\) CP asymmetries for each mode. Averaged values between Belle and BaBar are listed\(^5\)\(^7\)\(^8\).
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\[ A(B \to \eta'K^0) = \frac{1}{\sqrt{6}} \left[ (P + 2S + \frac{1}{3} P_{EW}) + 2(P^s + S^s - \frac{1}{3} P_{EW}^s) \right] V_{ts}^* V_{ts} \]

\[ A(B \to K^0\pi^0) = \frac{1}{\sqrt{2}} \left[ (P - P_{EW}) V_{ts}^* V_{ts} - CV_{us}^* V_{us} \right] . \]

Here, \( P \) and \( S \) represent \( b \to s(\bar{q}q) \) color-favored and \( b \to s(\bar{q}q) \to SU(3) \) singlet QCD penguin diagrams, respectively. \( P^s \) and \( S^s \) are the corresponding \( b \to s(s) \) type diagrams. \( C \) stands for color-suppressed tree diagram and \( P_{EW} \) is for electroweak (EW) penguin. For the parametrization, we follow the method\(^{10} \) which is very convenient, and useful to put a hierarchy assumption among the magnitude of the diagrams within the SM; \( |P|, |P^s| > |S|, |S^s|, |P_{EW}|, |P_{EW}^s| \) and \( |P V_{tb}^* V_{ts}| \gg |CV_{ub}^* V_{us}| \) and etc. If SU(3) flavor symmetry is exact, one can find easier relations between the parameters for \( b \to s(\bar{q}q) \) and \( b \to s(s) \), for example, \( P = P^s, S = S^s \). To decompose \( B \to \eta'K_s \) decay, we use a choice\(^{16} \) of the quark components of \( \eta' = (u\bar{u} + d\bar{d} + 2s\bar{s})/\sqrt{6} \), which is corresponding to the octet-singlet mixing angle \( \sim 19.5^\circ \).\(^{17} \) We distinguish \( B \to \) vector plus pseudoscalar meson (VP) decays from the \( B \) decays to two pseudoscalar mesons (PP) by adopting the tilde in corresponding parameters. In general, the parameters in \( B \to \phi K \) are not necessarily the same with those in \( B \to PP \) even if the exact SU(3) flavor symmetry is assumed.

Let us consider a special case, in which all the direct CP asymmetries are exactly zero. In this case we can estimate the allowed range of \( \sin 2\phi_D \) (see Eq. 1.4) using the experimental results in Table I as shown in Fig. 1. Ignoring the region from the ambiguity solution for \( \phi_1 \), \( \sin 2\phi_D \) seems to lie away from zero, taking a value around \(-0.3 \). If this is true, such a large weak decay phase must also affect other related decay modes. For example, if we measure, \textit{with enough precision}, the time-dependent CP asymmetry of \( B_s \to K^0\bar{K}^0 \), which is a pure \( b \to s \) QCD penguin process, then we could directly extract such a large new weak phase. Similarly, using \( B_s \to \eta'\pi^0 \), one can investigate existence of new weak phase in EW penguin sector. Therefore, in order to find the origin of new weak phase, precision-measurements of the related \( B_s \) decays are very important. Some of the corresponding \( B_s \) decay modes are listed in Table II. Because there is essentially no weak phase in \( B_s - \bar{B}_s \) mixing within
the SM, any sizable $S_f$ can directly indicate an existence of a weak phase from NP. Moreover, by comparing these decay modes, one may figure out the origin of the new CP phase. Even if some new phases enter the mixing process of $B_s$, one can still probe them by considering various modes simultaneously.

$$S_f = \sin(2\phi_1 + 2\phi_D)$$

$B_d \rightarrow \phi K^0$ & $B_s \rightarrow \phi \eta'$ & QCD and EW Penguins

$\eta'$ P & $B_d \rightarrow \eta' K^0$ & $B_s \rightarrow \eta' \pi^0$ & EW Penguin

PP & $B_d \rightarrow K^0 \pi^0$ & $B_s \rightarrow K^0 \pi^0$ & $b \rightarrow s$ QCD Penguin

$B_d \rightarrow K^0 K^0$ & $B_d \rightarrow K^0 K^0$ & $b \rightarrow d$ QCD Penguin

Table II. The $B_d$ and $B_s$ decay modes to VP, PP and $\eta'$ P, showing the origin of the weak decay phase $\phi_D$.

If there exist such NP effects in $b \rightarrow s$ penguin process, they might also appear in $b \rightarrow d$ penguin sector and so influence relevant decay modes such as $B \rightarrow \pi\pi$ decays. This may cause a serious concern for extracting $\phi_2$ from the time-dependent CP asymmetry of $B \rightarrow \pi\pi$. One could use $B_d \rightarrow K^0 \bar{K}^0$ mode to extract necessary information about such effects in $b \rightarrow d$ penguin diagrams. Time-dependent CP asymmetry of $B_d \rightarrow K^0 \bar{K}^0$ can also play an important role to understand the difference of $S_f$’s from $B \rightarrow J/\psi K^0$ and $b \rightarrow s$ penguin processes. In particular, this measurement will be useful to clarify the relations among the branching fractions and CP asymmetries of $B \rightarrow K\pi$ and $B \rightarrow \pi\pi$ modes which might contain a clue about the new weak phase in the penguin contributions.

Present experimental data gives $S_{\phi K} \simeq S_{\eta' K} \simeq S_{K^0 \pi^0} \sim 0.48$, hence we may
say that the current situation is fairly close to Case D. As can be seen in Fig. [1], the current experimental results seem to indicate that a sizable new CP phase \( \phi_D \) is needed to explain the discrepancy. Since the weak phases from the \( B - \bar{B} \) mixing are known to be all the same, the origin of the differences must lie in the decay processes. On the other hand, the direct CP asymmetries \( A_f \)'s are consistent with zero for all the modes. It can be controlled by the strong phase difference. Now we consider each case in detail.

Case A (with \( S_{J/\psi K} \approx S_{K^0\pi^0} \neq S_{\phi K} \approx S_{\eta' K} \))
In this case NP will appear only in \( b \to s\bar{s}s \) type processes. We parametrize its contribution as follows:

\[
(P^s + S^s - \frac{1}{3} P_{EW}^s)V_{tb}^*V_{ts} \Rightarrow A_{SM}^s (1 + r e^{i\delta} e^{i\theta}) ,
\]

where \( A_{SM} \) is the SM prediction. And \( r \) is the relative ratio of summed NP contributions to the SM contribution, \( \delta \) is the resultant NP strong phase relative to the SM, and \( \theta \) is the relative CP phase from NP. Strong phase \( \delta \) depends on the decay process, but weak phase \( \theta \) depends only on interaction type. For simplicity, we assume that the weak phase differences \( \theta \) for \( b \to s \) penguin type diagrams are same because these three modes are almost pure penguin processes.

Neglecting the \( C \) term, one can obtain

\[
A(B \to \phi K) = \tilde{A}_{SM}^s (1 + \tilde{r} e^{i\tilde{\delta}} e^{i\tilde{\theta}}) ,
\]

\[
A(B \to \eta' K^0) = \frac{1}{\sqrt{6}} \left[A_{SM} + 2A_{SM}^s (1 + r e^{i\delta} e^{i\theta}) \right] 
\equiv B_{SM} (1 + r_B e^{i\delta_B} e^{i\theta})
\]

where \( \tilde{\delta} \) and \( \delta \) are the relative strong phases and \( \theta \) is a CP phase from NP. Here we assume that the same new weak phase enters the two modes because its origin is the same type of penguin diagram. In the \( B_d \to \eta' K^0 \) decay, the re-defined parameters are

\[
B_{SM} = \frac{1}{\sqrt{6}} (2A_{SM}^s + A_{SM}) ,
\]

\[
B_{SM} r_B e^{i\delta_B} = \frac{2}{\sqrt{6}} A_{SM}^s r e^{i\delta}.
\]
where there is no NP contribution in $B \to K^{0} \pi^{0}$, because it is not $b \to s \bar{s}s$ process. Assuming that there is no direct CP violation in the SM and so $|A_{SM}| = |\overline{A}_{SM}|$, then the measurements are expressed as

$$Br_{\phi K} \propto |\tilde{A}_{SM}^{s}|^2(1 + \tilde{r}^2 + 2\tilde{r} \cos \delta \cos \theta),$$

$$A_{\phi K} \equiv - \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} = \frac{2\tilde{r} \sin \tilde{\delta} \sin \theta}{1 + \tilde{r}^2 + 2\tilde{r} \cos \delta \cos \theta},$$

$$S_{\phi K} \equiv \frac{2Im(e^{-2i\phi_{1}}A^{*}\overline{A})}{|A|^2 + |\overline{A}|^2} = \frac{2\tilde{r} \sin \phi_{1} + \tilde{r}^2 \sin 2(\phi_{1} + \theta) + 2\tilde{r} \cos \tilde{\delta} \sin(2\phi_{1} + \theta)}{1 + \tilde{r}^2 + 2\tilde{r} \cos \delta \cos \theta}. \tag{2.8}$$

The weak phase $\phi_{1}$ from the $B_{d}^{0} - \overline{B}_{d}^{0}$ mixing is supposed to be extracted from $B \to J/\psi K_{s}$ at good accuracy. Similarly, the expressions for $B \to \eta' K^{0}$ are obtained by

$$Br_{\eta' K} \propto |B_{SM}|^2(1 + r_{B}^2 + 2r_{B} \cos \delta^{B} \cos \theta),$$

$$A_{\eta' K} = \frac{2r_{B} \sin \delta^{B} \sin \theta}{1 + r_{B}^2 + 2r_{B} \cos \delta^{B} \cos \theta},$$

$$S_{\eta' K} = \frac{\sin 2\phi_{1} + r_{B}^2 \sin 2(\phi_{1} + \theta) + 2r_{B} \cos \delta^{B} \sin(2\phi_{1} + \theta)}{1 + r_{B}^2 + 2r_{B} \cos \delta^{B} \cos \theta}. \tag{2.11}$$

In Fig. 2 we show the allowed parameter space by using the current experimental constraints. According to our estimate, $\delta^{B}$ should be around $0^\circ$ or $180^\circ$ because the experimental data of $A_{\eta' K}$ is almost zero and the error is very small.

Fig. 2. The allowed region of the parameters $\tilde{\delta}$ and $\tilde{r}$ for $B \to \phi K^{0}$ decay (Left) and $\delta^{B}$ and $r_{B}$ for $B \to \eta' K_{S}$ decay (Right) for Case A. Here $\theta$ is assumed as a free parameter.

If we consider exact SU(3) flavor symmetry, we can obtain several relations among the parameters. Under the special condition, the strong phases should be same and also $|A_{SM}| = |\overline{A}_{SM}|$ so that

$$\delta = \delta^{B},$$

$$\frac{r_{B}}{r} = \frac{2A_{SM}^{s}}{2A_{SM}^{s} + A_{SM}} = \frac{2}{3}. \tag{2.12}$$
For simplicity, though it is not quite precise due to non-negligible SU(3) breaking effects and possible final state re-scattering effects\textsuperscript{*)}, we consider the following relations to get the rough estimation of the allowed region by reducing the number of parameters,

\begin{align}
  r &= \tilde{r}, \\
  \delta &= \tilde{\delta} = \delta^B.
\end{align}

Using these relations, we can extract the 3 parameters, \( r, \delta \) and \( \theta \) from the 4 measurements. The solutions (allowed regions) are shown in Fig. 3. These figures tell us we can not still so strictly constrain the parameter regions by the present experimental data but one can roughly see the dependence. Here we have to note that, as we mentioned before, this analysis has been made upon somewhat rough assumptions, therefore we may need more thorough considerations. As mentioned earlier, the penguin diagrams may be including different contributions for \( B \to VP \) and \( B \to PP \) so that we can not describe them with the same parameters. However, we find that these estimates are consistent with the allowed region for \( \sin 2\phi_D \) in Fig. 1 where \( \sin 2\phi_D \) lies around \(-0.3\). Considering the relation between \( \sin \phi_D \) and \( \sin \theta \) for \( \delta \sim 0^\circ \) (no direct CP asymmetry case), which is derived from \( 2\phi_D = \text{Arg} \frac{A(B^0 \to f_{CP})}{A(\bar{B}^0 \to \bar{f}_{CP})} \),

\begin{equation}
  \sin 2\phi_D = -2\frac{r}{1 + r^2 + 2r \cos \theta} \sin \theta (1 + r \cos \theta),
\end{equation}

one can see that the estimates, \( \sin \theta \sim 1 \) and \( r \sim 0.15 \) are consistent with those in Fig. 1. Thus in the sense seeing the rough estimation, one can find the dependence among the unknown parameters and may get some hints of new physics if we can find more accurate experimental data under this Case A\textsuperscript{**)}.  

\textsuperscript{*)} Here we are only trying to find a method to classify roughly the dependence of the parameters from NP effects, so that we neglect all those small effects.

\textsuperscript{**)} Note that we cannot directly compare the results within the allowed regions of Fig. 1. Here we use the comparison of Fig. 1 as a reference point to check whether our rough estimate can lead comparatively correct answer.
Case B (with $S_{J/ψK} \simeq S_{φK^0} \neq S_{K^0π^0} \simeq S_{η'/K}$)

In this case the possible source of NP could be in color-suppressed tree diagram or $b \to s\bar{q}q$ penguin sector. Although it may cause another difficulties, large color-suppressed tree contribution may come from NP or even in the SM due to our misunderstanding about how to estimate it. Actually, in recent several works\cite{13,21} on $B \to K\pi$, this possibility has been considered to explain the difference in the direct CP asymmetries of $B \to K^+\pi^-$ and $B \to K^+\pi^0$. The large $C$ contribution may also be useful to explain the discrepancies in the branching ratios of $B \to π^0π^0$, and etc. Therefore, we divide this case into two parts to discuss the case within the SM with unexpectedly large $C$, and the case with new weak phase from NP.

Case B-1 : The weak phase in the color-suppressed tree is only from CKM phase.

Considering penguin and tree type contributions separately, the decay amplitudes can be written as follows:

$$A(B \to η'/K^0) = A_p(1 - re^{iδ}e^{iφ_3}),$$
$$A(B \to π^0K^0) = A_p(1 + we^{iδ}e^{iφ_3}),$$

where $δ$ is a strong phase difference and $r$ and $w$ represent the relative ratios of the color-suppressed tree to the penguin contributions. Here we assume that the strong phase difference be the same in both modes. There are 3 unknown parameters and 1 weak phase for 4 measurements given by

$$A_{η'/K} = -\frac{2r \sin δ \sin φ_3}{1 + r^2 - 2r \cos δ \cos φ_3},$$
$$S_{η'/K} = \frac{\sin 2φ_1 + r^2 \sin 2(φ_1 + φ_3) - 2r \cos δ \sin(2φ_1 + φ_3)}{1 + r^2 - 2r \cos δ \cos φ_3},$$
$$A_{π^0K} = \frac{2w \sin δ \sin φ_3}{1 + w^2 + 2w \cos δ \cos φ_3},$$
$$S_{π^0K} = \frac{\sin 2φ_1 + w^2 \sin 2(φ_1 + φ_3) + 2w \cos δ \sin(2φ_1 + φ_3)}{1 + w^2 + 2w \cos δ \cos φ_3}. $$

Considering $\sin 2φ_1 \sim 0.69$, there should be some destructive contributions in the numerator of the above $S_j$ to satisfy the current experimental results. It could be done by requiring $90^° < (φ_1 + φ_3) < 180^°$ or controlling by the strong phase difference $δ$ in the third term. However, the explanation by the strong phase difference is somewhat problematic, because the signs of the terms with $\cos δ$ are different in the two decay modes so that its contribution will be always opposite. Requiring $90^° < (φ_1 + φ_3) < 180^°$ seems to be rather difficult because it needs large $φ_3$ compared to the current CKM bounds\cite{22}. And then one may consider a possibility that the strong phases are not the same in the two decay modes. But this again, we will need at least one large strong phase to reduce both $S_j$’s. In addition, the sign of the

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\*\*\* The recent estimates are $φ_3 = (59.8^{+4.9}_{-4.4})^°$ by CKM fitter Group\cite{22} and $φ_3 = (61.3 ± 4.5)^°$ by UT fit group\cite{23} which means that $φ_1 + φ_3 < 90^°$ is favored.
direct CP asymmetries could also give us some information about the strong phases, but the origin of such large differences will remain as a problem.

In fact, if we assume that the color-suppressed tree contribution \((C)\) is large\(^{18}\) to explain several discrepancies in \(B \to K\pi\) and \(\pi\pi\) decays\(^{13,19,20,21}\), it may also cause another discrepancy between \(B \to \phi K\) and the other \(b \to s\) penguin decay modes. As can be seen in Table 1, there is no such indication from experimental data. In contrast, if \(C\) is negligible, the direct CP violations will be almost zero and the indirect CP asymmetries are predicted as \(S_f = \sin 2\phi_1\) for all the three modes within the SM. In fact, considering the CKM factors together, the color-suppressed tree contribution, \(CV_{ub}^*V_{us}\), is indeed very small compared with QCD penguin contribution. Therefore, in order to explain the discrepancy between CP asymmetries of \(B \to J/\psi K\) and the other modes, it will be more appealing to have NP effects in \(b \to s\) penguin processes than requiring large \(C\) contributions within the SM.

As a temporary summery, recent experimental data seem not to prefer the explanation with only large \(C\) contribution within the SM. To explain them by using large \(C\) scenario, we need at least one more parameter like a new weak phase difference. In Case B-2, we will consider whether the new weak phase can help to explain this scenario.

**Case B-2 : Case B-1 plus a new physics weak phase.**

As a more general case, we now consider the case with the new physics weak phase, denoted by \(\theta\). We can consider that this case may include both cases: (a) Penguin sector has a new physics contribution with new weak phase and (b) Color-suppressed tree sector has a new weak phase. However, because \(C\) is only a tree contribution so that the case (b) may not be acceptable that it has new physics contribution with a new phase difference. Therefore, here we consider the case that the penguin has new physics contribution with a new weak phase as well as with a possibility that the magnitude of \(C\) may be also larger than ordinary estimate from the SM\(^*\).

Then, similar to the previous case, the four CP asymmetries are given by

\[
A_{\eta'K} = -\frac{2r \sin \delta \sin \theta}{1 + r^2 - 2r \cos \delta \cos \theta},
\]

\[
S_{\eta'K} = \frac{\sin 2\phi_1 + r^2 \sin 2(\phi_1 + \theta) - 2r \cos \delta \sin(2\phi_1 + \theta)}{1 + r^2 - 2r \cos \delta \cos \theta},
\]

\[
A_{\pi^0K} = \frac{2w \sin \delta \sin \theta}{1 + w^2 + 2w \cos \delta \cos \theta},
\]

\[
S_{\pi^0K} = \frac{\sin 2\phi_1 + w^2 \sin 2(\phi_1 + \theta) + 2w \cos \delta \sin(2\phi_1 + \theta)}{1 + w^2 + 2w \cos \delta \cos \theta}.
\]

\(^*\) The only difference from the previous case is the new physics phase \(\theta\). Hence, we may think that Case B-1 is a special case of Case B-2.
Using the constraints from Table 1 \( (A_{\eta'K} = 0.07 \pm 0.07, A_{K\pi} = 0.02 \pm 0.13 \) and \( S_{K\pi} = 0.31 \pm 0.26 ) \), we estimate the \( \theta \) and \( r \) dependencies by drawing \( S_{\eta'K} \) over \( r \) as in Fig. 4. This shows how much the negative contribution in \( S_{\eta'K} \) can be large by the new weak phase. Considering the current experimental bound on \( S_{\eta'K} \), we find that \( \theta \) should be larger than about 80°. In Fig. 4, we also show the allowed parameter spaces by using the current experimental data. Here \( w \) is treated as a free parameter. These figures tell us that the allowed region seems to be quite narrow and \( \theta \) should be larger than the current data of \( \phi_3 \). This may indicate that there should be a new weak phase and agrees with the discussion in Case B-1. We note that \( r \) (and \( w \)) must be also quite larger than the SM estimates which are \( \mathcal{O}(0.01) \).

Once again, this possibility of having large color-suppressed tree contribution can help explain several discrepancies, but it may not be readily acceptable in that large NP effects should be included in the tree diagram, because NP contributions are usually expected to appear through some loop effects.

### Fig. 4. The lower bound of \( S_{\eta'K} \) of the function of \( r \) for each \( \theta \) under constraints for \( A_{\eta'K} = 0.07 \pm 0.07, A_{K\pi} = 0.02 \pm 0.13 \) and \( S_{K\pi} = 0.31 \pm 0.26 \), where \( \delta \) and \( w \) are free parameters for Case B-2. The dotted lines show the experimental data of \( S_{\eta'K} \).

### Case C (with \( S_{J/\psi K} \simeq S_{\eta'K^0} \neq S_{\phi K} \simeq S_{K^{\pi\pi}} \)) – Possibly Accidental?

In this case, only the \( S_{\eta'K} \) should be different from the others. However, since the \( B \to \eta'K \) mode has all the types of penguin contributions and even color-suppressed tree, it can not be free from any NP effect appearing in other modes. Hence, it seems
unnatural and complicated to realize this case. But, this does not mean that we can simply exclude this case, because it really could be controlled by some complicated mechanism. If we consider this case, then all $S_f$’s will be different from each other. In the present work, we do not consider this case any further.

**Case D (with $S_{J/\psi K} \neq S_{K^{0,\pi,0}} \simeq S_{\phi K} \simeq S_{\eta' K}$)**

When we consider the present situation, $S_{\phi K} \simeq S_{\eta' K} \simeq S_{K^{0,\pi,0}}$ and $A_{\phi K} \simeq A_{\eta' K} \simeq A_{K^{0,\pi,0}} \sim 0$, it appears that Case D is the most plausible scenario. Therefore, we will consider this case thoroughly. Neglecting the color-suppressed tree contribution, the three modes can be parametrized as follows:

$$A(B \to \phi K) = \tilde{A}_{SM}(1 + \tilde{r}e^{i\tilde{\delta}}e^{i\theta}),$$

$$A(B \to \eta' K^0) = A_{SM}(1 + re^{i\delta}e^{i\theta}),$$

$$A(B \to \pi^0 K^0) = A_{SM}^w(1 + we^{i\delta^w}e^{i\theta}),$$

where $\tilde{r}, r$ and $w$ are the relative ratios of the NP effects to the ordinary penguin contributions. Here we assume that the new CP phase, denoted by $\theta$, is the same for all the modes. $\tilde{\delta}, \delta$ and $\delta^w$ are the strong phase differences for each modes. Using this parametrization, the time-dependent CP asymmetries are obtained by

$$A_{\phi K} = \frac{2\tilde{r} \sin \tilde{\delta} \sin \theta}{1 + \tilde{r}^2 + 2\tilde{r} \cos \tilde{\delta} \cos \theta},$$

$$S_{\phi K} = \frac{\sin 2\phi_1 + \tilde{r}^2 \sin 2(\phi_1 + \theta) + 2\tilde{r} \cos \tilde{\delta} \sin(2\phi_1 + \theta)}{1 + \tilde{r}^2 + 2\tilde{r} \cos \tilde{\delta} \cos \theta},$$

$$A_{\eta' K} = \frac{2r \sin \delta \sin \theta}{1 + r^2 + 2r \cos \delta \cos \phi_1},$$

$$S_{\eta' K} = \frac{\sin 2\phi_1 + \tilde{r}^2 \sin 2(\phi_1 + \theta) + 2\tilde{r} \cos \delta \sin(2\phi_1 + \theta)}{1 + \tilde{r}^2 + 2\tilde{r} \cos \delta \cos \phi_1},$$

$$A_{\pi^0 K} = \frac{2w \sin \delta^w \sin \theta}{1 + w^2 + 2w \cos \delta^w \cos \theta},$$

$$S_{\pi^0 K} = \frac{\sin 2\phi_1 + w^2 \sin 2(\phi_1 + \theta) + 2w \cos \delta^w \sin(2\phi_1 + \theta)}{1 + w^2 + 2w \cos \delta^w \cos \theta}.$$
Fig. 6. For Case D, the allowed region for $r$ and $\theta$ to satisfy $A_{\eta'K}, S_{\eta'K}, A_{K\pi}$ and $S_{K\pi}$ under relations $r = w$ (Left), which shows it comes from penguin diagrams, and $9r \sim w$ (Right), which comes from EW penguin.

QCD penguin sector\(^*)\), the parameters $r$ and $w$ can be estimated as

$$r = \frac{3X}{3P - 3X + 4S - \frac{1}{3}P_{EW}},$$
$$w = \frac{X}{P - X - P_{EW}}.$$

Then, they are roughly of the same order of magnitude,

$$r : w = 1 : 1,$$

(2.36)

so that we can reduce the number of unknown parameters and extract the information on the four parameters $r, w, \delta, \delta^w$ and $\theta$ from four measurements. The difference between $B \to \eta'K$ and $B \to K\pi$ comes only from the strong phases. If they have the same strong phase, there will be no difference in the measurements.

If NP shows up in the EW penguin sector, then

$$r = \left| \frac{\frac{1}{3}X}{3P + 4S - \frac{1}{3}(P_{EW} - X)} \right|,$$
$$w = \left| \frac{X}{P - (P_{EW} - X)} \right|.$$

Roughly speaking, in this case,

$$r : w = 1 : \left| \frac{9P + 12S - (P_{EW} - X)}{P - (P_{EW} - X)} \right| \sim 1 : \frac{9}{1 + \frac{8X}{9P + X}} = 1 : \frac{9}{\sqrt{1 + 64r^2 + 16r \cos \delta \cos \theta}}$$

(2.37)

\(^*)\text{Please note that the contribution of } P \text{ is already including NP contribution of } X, \text{ and the SM only contribution in } P \text{ should be } P - X.$
where $r$ is almost $|X/(9P)|$. For the above two cases with $w_r = 1$ and $w_r = \sqrt{1+64r^2+16r\cos\delta\cos\theta}$, the allowed regions for $r$ and $\theta$ are plotted in Fig. 6.

Our estimate shows that NP contributions must have a large weak phase to explain the present discrepancies. However, we need more precise experimental results to single out, hence understand the CP violation effects due to NP. Though our present analysis seems to be quite rough, at least, we expect one may find which case will be preferred by the results from $B$-factory experiments in near future. To extract the more definite hint about NP effects, we may have to add some extra information about the parameters from the other experimental data. In next section, we discuss how to classify the new physics contributions by adding the information of $B_s$ decays.

§3. Complementary Analysis through $B_s$ and $B_d$ decays

If the discrepancy in the indirect CP asymmetry $S_f$ is true, it will be more important to know where the source of the discrepancy is. As shown in the previous section, the differences among the $S_f$’s of $B \to \phi K$, $B \to \eta' K$ and $B \to K\pi$ could lead to some information about NP effects. However, if the situation is Case D, then we should be able to separate each contribution to find where the NP effects may come from. In this regard, using the time-dependent CP asymmetries of the $B_s$ decays, one can obtain further useful information. As listed in Table III, the $B_s \to K^0\bar{K}^0$ mode is almost a pure QCD penguin process, and the $B_s \to \eta'\pi^0$ is almost a pure EW penguin mode. If one of them is including a large weak phase, its effect should appear in the $S_f$. Therefore, any sizable difference between $S_{K^0\bar{K}^0}$ and $S_{\eta'\pi^0}$ will directly imply the different origin of the weak phases. The two processes can be expressed as

$$A(B_s \to K^0\bar{K}^0) = P V_{tb}^* V_{ts} \equiv |P V_{tb}^* V_{ts}| e^{i\delta} e^{i\phi_D(K^0\bar{K}^0)},$$

$$A(B_s \to \eta'\pi^0) = 2 \sqrt{6} P E W V_{tb}^* V_{ts} \equiv 2 \sqrt{6} |P E W V_{tb}^* V_{ts}| e^{i\delta} e^{i\phi_D(\eta'\pi^0)}. \quad (3.2)$$

Then, the indirect CP asymmetries are given as $S_{K^0\bar{K}^0} = \sin 2\phi_{D(K^0\bar{K}^0)}$ and $S_{\eta'\pi^0} = \sin 2\phi_{D(\eta'\pi^0)}$. The difference between $S_{K^0\bar{K}^0}$ and $S_{\eta'\pi^0}$ will lead directly to the difference between the angles $\phi_{D(K^0\bar{K}^0)}$ and $\phi_{D(\eta'\pi^0)}$, which may have different origins. To be consistent with the situation of Fig. 1, one or both of them should have non-negligible value under SU(3) flavor symmetry. Even if some new phase also comes in the $B_s - \bar{B}_s$ mixing process, nevertheless the difference will appear between them.

In Fig. 6, we summarize possible roles of the $B_s$ decays to classify the types of NP.

Similar analysis can be applied to the $B_d \to K^0\bar{K}^0$ mode which is a pure $b \to d$ QCD penguin process. The decay amplitude is expressed as follows:

$$A(B_d \to K^0\bar{K}^0) = P V_{tb}^* V_{td} \equiv |P V_{tb}^* V_{td}| e^{i\delta} e^{i(-\phi_1+\phi_{D(K^0\bar{K}^0)})}. \quad (3.3)$$
Then, the time-dependent CP asymmetry \( S^d_{K^0\bar{K}^0} \) is obtained by
\[
S^d_{K^0\bar{K}^0} = \sqrt{1 - A^2} \text{Im} \left[ e^{-2i\phi_1} \frac{A(B^0 \to K^0\bar{K}^0)\star A(\bar{B}^0 \to K^0\bar{K}^0)}{|A(B^0 \to K^0\bar{K}^0)| |A(\bar{B}^0 \to K^0\bar{K}^0)|} \right] = \sin(2\phi^d_{D(K^0\bar{K}^0)}),
\]
when the weak phase in the \( B_d - \bar{B}_d \) mixing is the same as the SM expectation \( \phi_1 \). Therefore, the observation of a sizable \( S^d_{K^0\bar{K}^0} \) may provide an evidence for the corresponding NP effect in \( b \to d \) QCD penguin sector. Furthermore, comparing \( S^d_{K^0\bar{K}^0} \) and \( S^s_{K^0\bar{K}^0} \), one can check whether the source of the new CP phase is in \( b \to s \) or \( b \to d \) penguin sector, or possibly in both sectors. Hence, these modes will be very important to understand in which processes new CP phases might exist.

In the actual analysis, however, there could be more uncertainties to extract the information than a naive expectation. To be more specific, let us consider \( B_d \to K^0\bar{K}^0 \) mode somewhat in detail. In the \( b \to d \) penguin process, there are three diagrams with different internal particles in the loop. Using the unitarity relation of CKM matrix, the amplitude will be decomposed as follows:
\[
A(B_d \to K^0\bar{K}^0) = (P_t - P_u)V_{tb}^*V_{td} + (P_c - P_u)V_{cb}^*V_{cd}
= |P_{tu}V_{tb}^*V_{td}|e^{i\delta}e^{-i(\phi_1 + \phi_{D_t})} - |P_{cu}V_{cb}^*V_{cd}|e^{i\delta}e^{i(\phi_{D_c})},
\]
where we assumed the direct CP asymmetry is absent so that there is no strong phase difference between the two terms. Then, we have
\[
S^d_{K^0\bar{K}^0} \equiv \sin(2\phi^d_{D(K^0\bar{K}^0)}) = \sin(2(Z - \phi_1)),
\]
where
\[
\tan Z = \frac{|P_{tu}V_{tb}^*V_{td}| \sin(\phi_1 - \phi_{D_t}) + |P_{cu}V_{cb}^*V_{cd}| \sin(-\phi_{D_u})}{|P_{tu}V_{tb}^*V_{td}| \cos(\phi_1 - \phi_{D_t}) - |P_{cu}V_{cb}^*V_{cd}| \cos(\phi_{D_u})}
= \tan(\phi_1 - \phi_{D_t}) + \frac{|P_{cu}V_{cb}^*V_{cd}| \sin(\phi_1 - \phi_{D_t} + \phi_{D_u})}{|P_{tu}V_{tb}^*V_{td}| \cos^2(\phi_1 - \phi_{D_t})} + O((P_{cu}/P_{tu})^2),
\]
Treating \( (P_{cu}/P_{tu}) \) as a small parameter\(^{24}\), the angle extracted from the time-dependent CP asymmetry will be
\[
\phi^d_{D(K^0\overline{K}^0)} \sim \phi_{Dt}.
\]

(3.8)

Considering SU(3) flavor symmetry, one can expect that \( \phi_{Dt} \) is also related to the angle \( \phi^s_{D(K^0\overline{K}^0)} \) extracted from \( B_s \to K^0\overline{K}^0 \). So we can check the consistency by comparing each other. However, we note that the analysis can be more difficult if the charming penguin contribution is not small enough to be simply neglected.

\section*{§4. Discussions and Conclusions}

Time-dependent CP asymmetries for several \( B^0 \) decay modes may include some fruitful information about weak phases, especially, from New Physics. Actually, the current experimental results from the \( B \) factories seem to be indicating a possibility of the presence of some NP effects in the \( b \to s \) penguin-dominated modes. As \( B \) factory experiments are accumulating data, the measurements are getting more precise and with probing more and more channels. So, in the near future, it is expected that the discrepancies will be confirmed or possibly turned out to be no discrepancy at an acceptable confidence level. If the \textit{currently-appearing} discrepancy is real, as a next step, we should consider how to determine which type of interactions it may come from. Although there are still remaining uncertainties, considering Belle and BaBar experimental results and taking the average over all the possible measurements with the same SM expectation, some discrepancies seem to be getting manifest as shown in the recent averaged data.\(^{8}\) But it is not sure whether one can take the average among all the \( b \to s \) penguin type modes, because the dependence of the diagrams may be somewhat different. In fact, in order to discuss the NP effects we have to distinguish the related modes by topological diagrammatic decomposition method.

In this work, we have considered \( B \to \phi K^0, B \to \eta' K^0 \) and \( B \to K^0\pi^0 \) decay modes. We have derived a systematic classification on possible NP dependencies appearing in time-dependent CP asymmetries and also investigated which type of diagrams should be including such new phases. According to the current experimental results for the three modes, there is no large discrepancy in the \( S_f \)'s within those three modes. If this situation continues to remain even after the data are sufficiently updated, it may be natural to infer that the new contribution should reside in their common diagrams. Under the present situation, it is difficult to extract more details about the common contributions because all the three modes are including QCD and EW penguins. In this regard, we have shown that \( B_s \) decay modes can be very useful. Using the time-dependent CP asymmetries of \( B_s \) decay modes such as \( B_s \to \phi\eta', B_s \to \eta'\pi^0 \) and \( B_s \to K^0\overline{K}^0 \), one may determine where the new CP phase comes from. If there are some discrepancies among the \( B_s \) modes, it can directly imply the different origin of the new CP phase, even if the \( B_s - \overline{B}_s \) mixing includes a new weak phase.

In the future hadron-collision experiments such as ATLAS and CMS at LHC, the production cross-section of \( B_s \) will be enormous, hence they will provide op-
opportunities to study $B_s$ decays in great details. For the above-mentioned decays $B_s \to \phi \eta'$ and $B_s \to \eta' \pi^0$, however, it is essential to detect $\pi^0$'s and photons with a good precision. Experimental environments of LHC may not be suited for this purpose. On the other hand, the $e^+e^-$ $B$-factory experiments, BaBar and Belle, show very good performances in the studies of final states involving $\pi^0$ and/or single photons. To study $B_s$ in the $e^+e^-$ collision, viable options are running at $Z^0$ or $\Upsilon(5S)$ resonance energies. But with LHC in operation, reviving the LEP for running at $Z^0$ resonance will be practically out of the question. In contrast, it may not be of much problem to change the beam energies of the current $B$ factories for operating at $\Upsilon(5S)$. Recently, CLEO measured that $\mathcal{B}(\Upsilon(5S) \to B^{(*)}B^{(*)}_s) = (21 \pm 3 \pm 9)%$. This, combined with $\sigma(e^+e^- \to \Upsilon(4S)) \approx 3 \times \sigma(e^+e^- \to \Upsilon(5S))$, tells us that we need approximately 15 times more integrated luminosity operating at $\Upsilon(5S)$ in order to obtain experimental sensitivities for $B_s$ decays corresponding to those of similar $B_d$ decays. The so-called “Super-$B$ factory”, with more than an order of magnitude improvement in the instantaneous luminosity appears to be indispensable for this study.

Moreover, we have also discussed that $B_d \to K^0\bar{K}^0$ mode can be used to probe the different dependence between $b \to s$ and $b \to d$ transition systems. Since the $B_d \to K^0\bar{K}^0$ mode is a pure QCD penguin process, one can investigate the NP effects in the QCD penguin sector alone. As the results for this mode are expected to appear in $B$ factories, possibly after upgraded to super-$B$ factory project we will get more fruitful information on CP physics in penguin sector in the near future.

Acknowledgments

The work of C.S.K. was supported in part by CHEP-SRC Program and in part by the Korean Research Foundation Grant funded by the Korean Government (MOEHRD) No. R02-2003-000-10050-0. The work of Y.J.K. was supported by the Korean Research Foundation Grant funded by the Korean Government (MOEHRD) No. KRF-2005-070-C00030. The work of J.L. was supported by the SRC program of KOSEF through CQUeST with Grant No. R11-2005-021. The work of T.Y. was supported by 21st Century COE Program of Nagoya University provided by JSPS.

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