U-spin Implication for $B_s$ Physics and New Physics

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With U-spin symmetry, $b \to s$ and $b \to d$ penguin decays could be a subtle probe of CP violating new physics contributions. We show that, for $B \to PP$ ($P$ stands for a pseudoscalar meson), the U-spin relation is expected to be violated for only one decay pair by assuming that new physics affects only $b \to s$ transition processes. We also very shortly discuss the polarizations of two types of U-spin pairs for $B \to VV$ ($V$ stands for a vector meson).

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1. Introduction

Within the past decade, several different experiments have been focusing on the measurements of CP violation in various flavor violating $B$ decays. The main aim is to test the Standard Model (SM) which contains only one source of CP violation. A definitive discrepancy between experimentally measured and theoretically predicted CP asymmetries in $B$ decays, if found, would indicate the presence of new CP violating sources beyond the SM.

According to a recent UTfit study about the $B_s$ mixing phase [1], together with updated data from Belle for $B_{u,d} \to \pi K$ [2], $b \to s$ transition is seemingly affected by CP violating new physics (NP). However, none of large discrepancies with the SM has been found in $b \to d$ phenomena at present [3]. In fact, the CP violation in $B_s \to \pi K$, recently measured by CDF, would agree with the SM expectation [4].

It is worth mentioning that the strong hint of NP is indicated in certain $b \to s$ CP violating phenomena. If the current observations are confirmed by further experimental improvements, what kind of NP scenario appears to be plausible? Throughout our presentation, we assume that U-spin symmetry reasonably holds among different $B$ decays. We then point out that the similar hint of CP NP can be found by comparing $B_d \to K^0\pi^0$ with $B_s \to \bar{K}^0\pi^0$. We also very shortly discuss the polarizations of $B_s \to K^{*}\bar{K}^{*0}$, $\phi\bar{K}^{*0}$.

2. U-spin symmetry and Standard Model

Sometime ago it was pointed out that, within the SM, a relation involving decay rates and direct CP asymmetries holds for the $B$ decay pairs that are related by U-spin [3, 6]. U-spin is the symmetry that places $d$ and $s$ quarks on an equal footing. The pairs associated with $B \to \pi K$ are listed in Table I as well as two pairs of neutral $B$ decays into two vector mesons, which are discussed in our presentation.

In the limit of U-spin symmetry, the effective Hamiltonian describing a $b \to d$ transition is equal to that of the corresponding $b \to s$ transition, where the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix are changed appropriately. With the CKM unitarity relation [7],

$$\text{Im}(V_{ub}^\dagger V_{ub} V_{ub}^\dagger V_{ub}^\dagger) = -\text{Im}(V_{us}^\dagger V_{ud} V_{us} V_{ud}^\dagger),$$

(1)

a perfect U-spin symmetry guarantees the following relation,

$$|A(B \to f)|^2 - |A(\bar{B} \to f)|^2 = -\left[|A(U \bar{B} \to U f)|^2 - |A(U \bar{B} \to U f)|^2\right],$$

(2)

in which $U$ is the U-spin operator that transposes $d$ and $s$ quarks. This expression can be written as

$$\frac{A_{CP}^{\text{dir}}(\text{decay } #1)}{A_{CP}^{\text{dir}}(\text{decay } #2)} = \frac{BR(\text{decay } #2)}{BR(\text{decay } #1)},$$

(3)

where $A_{CP}^{\text{dir}}$ and $BR$ refer to the direct CP asymmetry and branching ratio, respectively, and where decays $\#1,2$ are the $b \to d$ and $b \to s$ decays, in either order, related by U-spin. Note that if decays $\#1,2$ include $B_d$ and $B_s$ mesons, there is an additional factor on the right-hand side taking the lifetime difference into account.

Let us now look at pair $\#1$. Ref. [3] has paid special attention to this pair and argued about a test of the SM vs. NP.

Table I The pairs of $B$ decays which are related by U-spin. $\#1$-$\#3$ are for $B$ decays into two pseudoscalar mesons [4], while $\#4$-$\#5$ are for $B$ decays into two vector mesons.

| $B \to s$ | $B \to d$ |
|---|---|
| $B_d^0 \to K^+\pi^-$ | $\bar{B}_s^0 \to \pi^+K^-$ |
| $B_d^0 \to K^0\pi^0$ | $B_s^0 \to \bar{K}^{*0}\pi^0$ |
| $B_s^+ \to K^0\pi^+$ | $B_s^+ \to \bar{K}^0K^+$ |
| $B_s^0 \to K^{*0}\bar{K}^{*0}$ | $B_s^0 \to B_s^0 \to K^{*0}\bar{K}^{*0}$ |
| $B_s^0 \to \phi K^{*0}$ | $B_s^0 \to \phi K^{*0}$ |
Table II  Branching ratios and direct CP asymmetries for the $B \to \pi K$ decays. The data is taken from Ref. [2].

| Mode | $BR[10^{-6}]$ | $A_{CP} [%]$ |
|------|-------------|-------------|
| $B^+ \to \pi^+ K^0$ | $23.1 \pm 1.0$ | $0.9 \pm 2.5$ |
| $B^+ \to \pi^0 K^+$ | $12.9 \pm 0.6$ | $5.0 \pm 2.5$ |
| $B_d^0 \to \pi^- K^+$ | $19.4 \pm 0.6$ | $-0.7 \pm 1.2$ |
| $B_d^0 \to \pi^0 K^0$ | $9.9 \pm 0.6$ | $-14 \pm 11$ |
| $B_s \to \pi^+ K^-$ | $5.00 \pm 1.25$ | $39 \pm 17$ |

The decay amplitudes for pair #1 are given by

\[
A(B_d \to K^+ \pi^-) = V_{ub}V_{us}A_u^{(s)} + V_{cd}V_{cs}^{*}A_c^{(s)},
\]

\[
A(B_s \to \pi^+ K^-) = V_{ub}V_{us}A_u^{(d)} + V_{cd}V_{cs}^{*}A_c^{(d)},
\]

where $A_u^{(q)}$ and $A_c^{(q)}$, with $q = s, d$, are strong decay factors from tree and penguin amplitudes. The index $q$ refers to the $b \to q$ transition in the penguin diagrams. To date there is no firm evidence, in $B$ decays into two pseudoscalar mesons, that nonfactorizable contributions (including penguin annihilation effects [9]) are sizable. We therefore employ a picture where the nonfactorizable terms are simply higher-order contributions (including penguin annihilation effects [9]) that nonfactorizable terms are simply higher-order contributions and less important than the (naive) factorizable terms. As long as this picture reasonably holds, the U-spin breaking effects are expected to be small. One then finds that $A_u^{(q)} = A_u^{(d)} = A_u$ and $A_c^{(q)} = A_c^{(d)} = A_c$ are good approximations, and Eq. (3) is satisfied for pair #1 within the SM. In the following discussion, we basically follow the same strategy.

Recent experimental results for $B \to \pi K$ are collected in Table II. Using these data, we can estimate the U-spin relation for pair #1, and it turns out

\[
A_{dir}(B_d^0 \to \pi^+ K^-) = 4.2 \pm 2.0,
\]

\[
A_{dir}(B_d^0 \to \pi^- K^+) = 3.9 \pm 1.0.
\]

Table II  Branching ratios and direct CP asymmetries for the $B \to \pi K$ decays. The data is taken from Ref. [2].

Although the error is still large, the two ratios are nearly equal. It is remarkable that the Eq. (3) is satisfied for pair #1, i.e., there is apparently no evidence of NP in this pair. Is the fact found in pair #1 contradictory to other clues observed in different $b \to s$ phenomena? We would like to emphasize that this could be another interesting hint for NP.

### 3. Implication for $B_s$ Physics

As we mentioned, to date there has been no visible discrepancies with the SM in $b \to d$ decays. We follow this experimental indication and assume that the NP appears only in $b \to s$ decays but does not affect $b \to d$ decays.

There are many NP operators which can contribute to $b \to s$ decays. However, it was recently shown in Ref. [10] that this number can be reduced considerably. At the quark level, each NP contribution to the decay $B \to f$ takes the form $\langle f | O_{NP}^{q_f} | B \rangle$, where $O_{NP}^{q_f}$ represents Lorentz structures, and color indices are suppressed. Each NP matrix element can have its own weak and strong phase. Now, it should be mentioned that the idea of small NP strong phases can be justified [11] [12]. We then further simplify our study by neglecting all NP strong phases. One can then combine all NP matrix elements into a single NP amplitude, with a single weak phase:

\[
\sum \langle f | O_{NP}^{q_f} | B \rangle = A^q e^{i \Phi_q}.
\]

In fact, for $b \to s$ decays, there are two classes of NP operators, differing in their color structure: $\bar{s}_a \Gamma_1 b \bar{q}_3 \Gamma_\beta q_\beta$ and $\bar{s}_a \Gamma_1 b \bar{q}_3 \Gamma_\beta q_\beta$. The first class of NP operators contributes with no color suppression to final states containing $\bar{q}q$ mesons. Similarly, for final states with $\bar{s}q$ mesons, the roles of the two classes of operators are reversed, but there is a suppression factor of $1/N_c$. As in Ref. [11], we denote by $A^{uq} e^{i \Phi_u}$ and $A^{cq} e^{i \Phi_c}$ the sum of NP operators which contribute to final states involving $\bar{q}q$ and $\bar{s}q$ mesons, respectively (the primes indicate a $b \to s$ transition). Here, $\Phi_u$ and $\Phi_c$ stand for the NP weak phases.

Let us now return to $B_{u,d} \to \pi K$ decays in order to study the effect of the NP operators on $b \to s$ transitions. In Ref. [13], the relative sizes of the SM $B_{u,d} \to \pi K$ diagrams were roughly estimated as

\[
1 : |P'_c)|, \quad O(\bar{\lambda}) : |T'|, \quad |P'_{EW}|,
\]

\[
O(\bar{\lambda}^2) : |C'|, \quad |P'_{uw}|, \quad |P'_{cw}|
\]

where $\bar{\lambda} \sim 0.2$. The diagrams $T'$ and $C'$ are the color-favored and color-suppressed trees, $P'_c$ and $P'_{uw}$ are the gluonic penguins, and $P'_{cw}$ are the color-favored and color-suppressed electroweak penguins, respectively. Especially for the ratio $|C'/T'|$, the SM predictions from different calculation approaches would agree to the naive estimation of Eq. (7) [9] [14] [13].

Putting all diagrams together, Ref. [16] had performed a fit by using the 2006 $B \to \pi K$ data [3]. A good fit is found, however, this fit requires $|C'/T'| \sim 1.6 \pm 0.3$ which is much larger than the estimates of Eq. (7). This might imply that the $B \to \pi K$ fit including NP amplitudes is necessary. If one ignores the small $O(\bar{\lambda}^2)$ diagrams, the $B \to \pi K$ amplitudes (i, j are electric charges) can be written [11]

\[
A^{+0} = -P'_c + A^{u,c} e^{i \Phi_u,c}
\]

As we mentioned, to date there has been no visible discrepancies with the SM in $b \to d$ decays. We follow this experimental indication and assume that the NP
where $\gamma$ is the SM weak phase and $A^{\text{comb}}_{\text{trans}} e^{i\Phi^\text{C}} \equiv -A^{u,d}_c e^{i\Phi^\text{C}} + A^{d,u}_c e^{i\Phi^\text{C}}$. It is not possible to distinguish the two component amplitudes in $B \rightarrow \pi K$ decays. We therefore denote all possible NP amplitudes in $B \rightarrow \pi K$ as $A^{u,d}_c e^{i\Phi^\text{C}}, A^{d,u}_c e^{i\Phi^\text{C}}$, and $A^{\text{comb}} e^{i\Phi^\text{C}}$.

The three NP operators were then included in the $B \rightarrow \pi K$ fit in Ref. [16], one at a time. It was found that the fit remained poor if $A^{u,d}_c e^{i\Phi^\text{C}}$ or $A^{d,u}_c e^{i\Phi^\text{C}}$ was added. That is, these NP operators can be large or small. If we neglect $A^{u,d}_c e^{i\Phi^\text{C}}$ and $A^{d,u}_c e^{i\Phi^\text{C}}$ by assuming that they are small, a good fit was obtained through a large value of $A^{\text{comb}} e^{i\Phi^\text{C}}$. It is worth mentioning that, if we look at the amplitude $\bar{A}^{\pm}$ describing $B_d^0 \rightarrow \pi^- K^+$, the amplitude does not contain NP effects because of $A^{c,u}_c e^{i\Phi^\text{C}} = 0$. As seen in Eq. (3), the current data is consistent with the SM prediction. It seemingly supports the idea that $A^{c,u}_c e^{i\Phi^\text{C}}$ is small. Therefore, we expect that $A^{\text{comb}} e^{i\Phi^\text{C}}$ brings sizable effects into the $b \rightarrow s$ transition, while $A^{c,u(d)}_{a(d)}$ is less important.

In this case, it turns out that only the decay pair #2 can be significantly affected by NP. We would like to repeat that this consequence is consistent with what we have found in Sec. 2. The pair #2, therefore, should be looked at more closely although the precise measurements of time-dependent CP asymmetries for those decays would be challenging.

Before closing this section, we briefly refer to the U-spin implications for $B_s \rightarrow K^{*0}\bar{K}^{*0}$ and $B_s \rightarrow \phi\bar{K}^{*0}$. The $B_d \rightarrow \phi\bar{K}^{*0}$ had brought forth the polarization puzzle - the longitudinal and transverse components are roughly equal size, which cannot be explained by the naive factorization calculation within the SM (nSM). There are a lot of studies dealing with this puzzle [17]. Let us now assume that the transverse amplitude is expressed as a single dominant contribution which arises from beyond the nSM, and it is nonfactorizable. As long as U-spin symmetry reasonably holds among the strong decay factors of the final state $V V$, the transverse components in pairs #4 and #5 can be simply given by

\[
A_\gamma(B_s^0 \rightarrow K^{*0}\bar{K}^{*0}) \approx \frac{|V_{ts}|}{|V_{td}|} f_0^0 f_0^0, \\
A_\gamma(B_s^0 \rightarrow \phi\bar{K}^{*0}) \approx \frac{|V_{ts}|}{|V_{td}|} f_0^0 f_0^0. \tag{9}
\]

Because the final states are self-conjugate, pairs #4 and #5 are expected to provide better results in terms of theoretical uncertainties. Consequently, one has

\[
\frac{f_t(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})}{f_t(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})} \approx 28.4 \pm 7.2 \frac{BR(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})}{BR(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})}, \\
\frac{f_t(B_s^0 \rightarrow \phi\bar{K}^{*0})}{f_t(B_s^0 \rightarrow \phi\bar{K}^{*0})} \approx 18.8 \pm 4.8 \frac{BR(B_s^0 \rightarrow \phi\bar{K}^{*0})}{BR(B_s^0 \rightarrow \phi\bar{K}^{*0})}. \tag{10}
\]

However, they might not be robust estimates since U-spin breaking in nonfactorizable contributions would be more complicated and it might be large [18].

4. Summary

There are recent intriguing studies regarding whether a strong hint that implies NP in $b \rightarrow s$ transition processes would be observed. With U-spin symmetry, we speculated on the implications for $B_s$ decays.

Taking the fit results in Ref. [16] into account, only one NP amplitude is found to be large. We have shown that, Eq. (3) is expected to be violated by only one decay pair: $B_d^0 \rightarrow K^{*0}\pi^0$ and $B_s^0 \rightarrow \phi\bar{K}^{*0}$.

We also shortly referred to the U-spin implications for the polarizations of $B_s \rightarrow K^{*0}\bar{K}^{*0}, \phi\bar{K}^{*0}$. In the limit of U-spin symmetry, assuming the particular scenario, the transverse components for $B_s \rightarrow K^{*0}\bar{K}^{*0}, \phi\bar{K}^{*0}$ can be estimated with relatively less uncertainties.

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