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Possible Implications of Small or Large CP Violation in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ Decays

XING Zhi-Zhong[1]

(Institute of High Energy Physics, The Chinese Academy of Sciences, Beijing 100039, China)

Abstract We argue that a small or large CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ decays, which seems to be favored by the recent BaBar or Belle data, might hint at the existence of new physics in $B_d^0 - \bar{B}_d^0$ mixing. We present a model-independent framework to show how new physics modifies the standard-model CP-violating asymmetry $\mathcal{A}_{\psi K_S}^{SM}$. We particularly emphasize that an experimental confirmation of $\mathcal{A}_{\psi K_S} \approx \mathcal{A}_{\psi K_S}^{SM}$ must not imply the absence of new physics in B_d^0-$\bar{B}_d^0$ mixing.

Key words B-meson dacay, CP violation new physics, B_d^0-$\bar{B}_d^0$ mixing

Recently the BaBar and Belle Collaborations have reported their new measurements of the CP-violating asymmetry in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ decays:

$$\mathcal{A}_{\psi K_S} = \begin{cases} 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst}) & (\text{BaBar}^{[1]}) \\ 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}) & (\text{Belle}^{[2]}) \end{cases}, \tag{1}$$

The central values of these two measurements are apparently different from that of the previous CDF measurement, $\mathcal{A}_{\psi K_S} = 0.79 \pm 0.42$[3]; and they are also different from the result obtained from global analyses of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle in the standard model, $\mathcal{A}_{\psi K_S}^{SM} = 0.75 \pm 0.06$[4]. In view of the error bars associated with the BaBar and Belle measurements, it remains too early to claim any serious discrepancy between the experimental result and the standard-model prediction. Nevertheless, one cannot rule out the possibility of $\mathcal{A}_{\psi K_S} < \mathcal{A}_{\psi K_S}^{SM}$ or $\mathcal{A}_{\psi K_S} > \mathcal{A}_{\psi K_S}^{SM}$. A small or large CP-violating asymmetry in $B_d \to J/\psi K_S$ decays should be a clean signal of new physics beyond the standard model.

The purpose of this paper is two-fold. First, we present a model-independent framework to show how new physics in B_d^0-$\bar{B}_d^0$ mixing may modify the standard-model quantity $\mathcal{A}_{\psi K_S}^{SM}$. We find that the possible deviation of $\mathcal{A}_{\psi K_S}$ from $\mathcal{A}_{\psi K_S}^{SM}$ can fully be described in terms of three independent parameters, including the magnitude and phase of the new-physics contribution to B_d^0-$\bar{B}_d^0$ mixing. Second, we point out that the equality $\mathcal{A}_{\psi K_S} = \mathcal{A}_{\psi K_S}^{SM}$ itself must not mean the absence of new physics in B_d^0-$\bar{B}_d^0$ mixing. Indeed there may exist a specific parameter space for the new-physics contribution to B_d^0-$\bar{B}_d^0$ mixing, in which the value of $\mathcal{A}_{\psi K_S}$ coincides with that of $\mathcal{A}_{\psi K_S}^{SM}$. Hence measuring the CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ alone is neither enough to test the standard model nor enough to constrain the possible new physics in B_d^0-$\bar{B}_d^0$ mixing.

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1) E-mail: xingzz@mail.ihep.ac.cn

It is well known that the CP asymmetry $\mathcal{A}_{\psi K_S}$ arises from the interplay of the direct decays of B_d^0 and $\bar{B}_d^0$ mesons, the B_d^0-$\bar{B}_d^0$ mixing in the initial state, and the K^0-$\bar{K}^0$ mixing in the final state[5]:

$$\mathcal{A}_{\psi K_S} = -\operatorname{Im}\left(\frac{q}{p}\cdot\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\cdot\frac{q_K^*}{p_K^*}\right), \tag{2}$$

where V_{cb} and V_{cs} are the CKM matrix elements, p and q are the B_d^0-$\bar{B}_d^0$ mixing parameters, p_K and q_K are the K^0-$\bar{K}^0$ mixing parameters, and the minus sign on the right-hand side of Eq. (2) comes from the CP-odd eigenstate $J/\psi K_S$. In this expression the tiny penguin contributions to the direct transition amplitudes, which may slightly modify the ratio$(V_{cb}V_{cs}^*)/(V_{cb}^*V_{cs})$[6], have been neglected. Within the standard model, $q_K/p_K \approx 1$, $q/p \approx V_{td}/V_{td}^*$ and $(V_{cb}V_{cs}^*)/(V_{cb}^*V_{cs}) \approx 1$ are excellent approximations in the standard parametrization of the CKM matrix[7]. Therefore one obtains $\mathcal{A}_{\psi K_S}^{SM} \approx -\operatorname{Im}(V_{td}/V_{td}^*) \approx \sin 2\beta$, where $\beta \equiv \arg[-(V_{cb}^*V_{cd})/(V_{tb}^*V_{td})] \approx \arg(-V_{td}^*)$ is one of the three inner angles of the CKM unitarity triangle[7]. A recent global analysis of the quark flavor mixing data and the CP-violating observables in the kaon system yields $\sin 2\beta = 0.75 \pm 0.06$[4].

If the measured value of $\mathcal{A}_{\psi K_S}$ deviates significantly from the standard-model prediction $\mathcal{A}_{\psi K_S}$, it is most likely that the B_d^0-$\bar{B}_d^0$ mixing phase q/p consists of unknown new physics contributions. Of course there may also exist new physics in K^0-$\bar{K}^0$ mixing, contributing a non-trivial complex phase to $\mathcal{A}_{\psi K_S}$ through q_K/p_K. It is quite unlikely that the tree-level W-mediated decays of B_d^0 and $\bar{B}_d^0$ mesons are contaminated by any kind of new physics in a significant way[8].

To be specific, we assume that a possible discrepancy between $\mathcal{A}_{\psi K_S}$ and $\mathcal{A}_{\psi K_S}^{SM}$ mainly results from new physics in B_d^0-$\bar{B}_d^0$ mixing. We therefore write down the ratio q/p in terms of the off-diagonal elements of the 2×2 B_d^0-$\bar{B}_d^0$ mixing Hamiltonian:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}} \text{ with } M_{12} = M_{12}^{SM} + M_{12}^{NP} \tag{3}$$

and $\Gamma_{12} = \Gamma_{12}^{SM}$. Note that $|M_{12}| \gg |\Gamma_{12}|$ is expected to hold both within and beyond the standard model, thus we have $q/p \approx \sqrt{M_{12}^*/M_{12}}$ as a good approximation. The relative magnitude and the phase difference between the new-physics contribution M_{12}^{NP} and the standard-model contribution M_{12}^{SM} are in general unknown. By definition, we may take $|M_{12}| = \Delta M/2$, where $\Delta M = (0.487 \pm 0.014)$ ps^{-1} is the experimentally measured mass difference between two mass eigenstates of B_d mesons[7]. Then we parametrize M_{12}^{SM}, M_{12}^{NP} and M_{12} in the following way:

$$M_{12}^{SM} = R_{SM}e^{i2\beta}\frac{\Delta M}{2},\quad M_{12}^{NP} = R_{NP}e^{i2\theta}\frac{\Delta M}{2},\quad M_{12} = e^{i2\phi}\frac{\Delta M}{2}, \tag{4}$$

where R_{SM} and R_{NP} are real and positive parameters, θ represents the new-physics phase, and ϕ denotes the effective (overall) phase of B_d^0-$\bar{B}_d^0$ mixing. Solving Eqs. (3) and (4), we obtain

$$R_{NP} = -R_{SM}\cos 2(\theta - \beta) \pm \sqrt{1 - R_{SM}^2\sin^2 2(\theta - \beta)}\ . \tag{5}$$

There exist two possible solutions for R_{NP}, corresponding to $(\pm)$ signs on the right-hand side of Eq. (5). Numerically, $R_{SM} > 0$ and $R_{NP} \geq 0$ must hold for either solution.

Although R_{SM} can be calculated in the box-diagram approximation, its value may involve quite large uncertainties arising from the hadronic matrix element $\langle B_d^0 | \bar{b}\gamma_\mu(1 - \gamma_5)d | \bar{B}_d^0 \rangle$. Nevertheless, R_{SM} is in general expected to be close to unity, no matter what kind of new physics is hidden in B_d^0-$\bar{B}_d^0$ mixing[9]. Note that $R_{SM} = 1$ must not lead to $R_{NP} = 0$. There is another solution, $R_{NP} = -2\cos 2(\theta - \beta)$ with $\cos 2(\theta - \beta) \leq 0$, corresponding to $R_{SM} = 1$. On the contrary, $R_{NP} = 0$ must result in $R_{SM} = 1$, as indicated by Eq. (5).

With the help of Eqs. (3) and (4), we recalculate the CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ and arrive at the following result:

$$\mathcal{A}_{\psi K_S} = \sin(2\phi) = R_{SM}\sin(2\beta) + R_{NP}\sin(2\theta) . \tag{6}$$

Note that R_{NP}, R_{SM}, β, and θ are dependent upon one another through Eq. (5). Of course, $|\mathcal{A}_{\psi K_S}| \leq 1$ holds within the allowed parameter space of R_{NP} and θ. The ratio of $\mathcal{A}_{\psi K_S}$ to $\mathcal{A}^{SM}_{\psi K_S}$ is given as

$$\xi_{\psi K_S} \equiv \frac{\mathcal{A}_{\psi K_S}}{\mathcal{A}^{SM}_{\psi K_S}} \approx \frac{\sin(2\phi)}{\sin(2\beta)} = R_{SM} + R_{NP}\frac{\sin(2\theta)}{\sin(2\beta)} . \tag{7}$$

In the literature (e.g., Ref. [4]), the value of $\mathcal{A}^{SM}_{\psi K_S} \approx \sin 2\beta$ is obtained from a global analysis of the experimental data on $|V_{ub}/V_{cb}|$, B^0_d-$\bar{B}^0_d$ mixing, B^0_s-$\bar{B}^0_s$ mixing, and CP violation in K^0-$\bar{K}^0$ mixing. The key assumption in such analyses is that there is no new-physics contribution to the K^0-$\bar{K}^0$, B^0_d-$\bar{B}^0_d$, and B^0_s-$\bar{B}^0_s$ mixing systems. If new physics does contribute significantly to the heavy meson-antimeson mixing instead of the light one, one has to discard the direct experimental data on B^0_d-$\bar{B}^0_d$ mixing and B^0_s-$\bar{B}^0_s$ mixing in analyzing the CKM unitarity triangle. In this case, the resultant constraint on $\sin 2\beta$ becomes somehow looser. One may observe, from the figures of the CKM unitarity triangle in Refs. [4,7], that $0.6 \leq \sin 2\beta \leq 0.8$ is a quite generous range constrained by current data on $|V_{ub}/V_{cb}|$ and CP violation in K^0-$\bar{K}^0$ mixing. Given such a generously allowed region for $\mathcal{A}^{SM}_{\psi K_S}$, we conclude that $\xi_{\psi K_S} > 0$ is definitely assured. Using $\mathcal{A}^{SM}_{\psi K_S} = 0.75 \pm 0.06$[4] for illustration, we obtain $\xi_{\psi K_S} = 0.79 \pm 0.26$ (BaBar) or 1.32 ± 0.30 (Belle). We see that the BaBar measurement seems to indicate $\xi_{\psi K_S} < 1$, while the Belle measurement seems to imply $\xi_{\psi K_S} > 1$. If either possibility could finally be confirmed with more precise experimental data from B-meson factories, it would be a very clean signal of new physics[10]. If the further data of both BaBar and Belle Collaborations turn to coincide with each other and lead to $\xi_{\psi K_S} \approx 1$, however, one cannot draw the conclusion that there is no new physics in B^0_d-$\bar{B}^0_d$ mixing.

Now let us show why $\mathcal{A}_{\psi K_S} = \mathcal{A}^{SM}_{\psi K_S}$ must not imply the absence of new physics in B^0_d-$\bar{B}^0_d$ mixing. Taking $\xi_{\psi K_S} = 1$ and using Eq. (5), we obtain the following equation constraining the allowed values of θ:

$$(1 + R_{SM})\tan^2 2\theta - 2R_{SM}\tan 2\beta \tan 2\theta - (1 - R_{SM})\tan^2 2\beta = 0 . \tag{8}$$

Then it is straightforward to find out two solutions for $\tan 2\theta$:

$$\tan 2\theta = \tan 2\beta \quad \text{and} \quad \tan 2\theta = \tan 2\beta \frac{R_{SM} - 1}{R_{SM} + 1} . \tag{9}$$

Note that the first solution corresponds to $R_{SM} + R_{NP} = 1$. The second solution implies that $|\tan 2\theta| \ll \tan 2\beta$ may hold, if R_{SM} is remarkably close to 1. Although the afore-obtained region of θ is quite specific, it does exist and give rise to $\xi_{\psi K_S} = 1$. Therefore, an experimental confirmation of $\xi_{\psi K_S} \approx 1$ cannot fully rule out the possibility of new physics hidden in B^0_d-$\bar{B}^0_d$ mixing.

Theoretically, the information on R_{NP} and θ can only be obtained from specific models of new physics (e.g., the supersymmetric extensions of the standard model[10]). An interesting possibility is that the new-physics contribution conserves CP (i.e., $\theta = 0$) and all observed CP-violating phenomena in weak interactions are attributed to the non-trivial phase in the CKM matrix. In this scenario, we obtain $\mathcal{A}_{\psi K_S} = \sin(2\phi) = R_{SM}\sin(2\beta)$. Obviously $\mathcal{A}_{\psi K_S}/\mathcal{A}^{SM}_{\psi K_S} = R_{SM} \leq 1$ is required, in order to understand the present BaBar measurements.

It becomes clear that the measurement of $\mathcal{A}_{\psi K_S}$ itself is not enough to test the self-consistency of the standard model or to pin down possible new physics hidden in B_d^0-$\bar{B}_d^0$ mixing. For either purpose one needs to study the CP-violating asymmetries in some other nonleptonic B-meson decays, although most of them are not so clean as B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ decays in establishing the relations between the CP-violating observables and the fundamental CP-violating parameters.

In summary, we have discussed possible implications of a small or large CP-violating asymmetry in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ decays. While such an effect could be attributed to new physics in K^0-$\bar{K}^0$ mixing, it is most likely to result from new physics in B_d^0-$\bar{B}_d^0$ mixing. Model-independently, we have formulated the basic features of new-physics effects on CP violation in $B_d \to J/\psi K_S$. We have also pointed out that an experimental confirmation of $\mathcal{A}_{\psi K_S} \approx \mathcal{A}_{\psi K_S}^{SM}$ must not imply the absence of new physics in B_d^0-$\bar{B}_d^0$ mixing. An extensive study of all hadronic B-meson decays and CP asymmetries is desirable, in order to test the standard model and probe possible new physics at some higher energy scales.

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弱衰变 $B_d \to J/\psi K_S$ 中的 CP 破坏与新物理

邢志忠[1)]
（中国科学院高能物理研究所 北京 100039）

摘要 最近 BaBar 与 Belle 国际合作组对弱衰变 $B_d \to J/\psi K_S$ 中的 CP 破坏测量结果似乎暗示有新物理存在于 B_d^0-$\bar{B}_d^0$ 混合. 为此给出一个模型无关的分析，以说明新物理对标准模型结果的可能修正. 特别强调，即使实验证明 $B_d \to J/\psi K_S$ 中的 CP 破坏效应与标准模型的预言相符，仍然有可能存在新物理.

关键词 B 衰变 CP 破坏 新物理 B_d^0-$\bar{B}_d^0$ 混合

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1) E-mail: xingzz@mail.ihep.ac.cn