CP Asymmetry in $B \to \phi K_S$ Decays in Left-Right Models and its Implications for B_s Decays

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In left-right models the gluonic penguin contribution to $b \to s\bar{s}s$ transition is enhanced by m_t/m_b due to the presence of $(V + A)$ currents and by large values of loop functions. Together those effects may overcome the suppression due to the small left-right mixing angle $\xi \lesssim 0.013$. Two independent new phases in the $B \to \phi K_S$ decay amplitude appearing in a large class of left-right models can modify the time-dependent *CP* asymmetry in this decay mode by $\mathcal{O}(1)$ and explain the recent *BABAR* and Belle *CP* asymmetry measurements in this channel. This scenario implies observable deviations from the standard model also in B_s decays which could be measured at Tevatron and LHC.

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The measurements of time-dependent asymmetries in $B \to J/\psi K_S$ have revealed *CP* violation in the *B* system. The observed world average of $\sin 2\beta$ [1],

$$\sin 2\beta_{J/\psi K} = 0.734 \pm 0.054, \qquad (1)$$

agrees well with the standard model (SM) prediction and indicates that the Kobayashi-Maskawa (KM) mechanism [2] is likely the dominant source of *CP* violation also in this process. Nevertheless, this result does not exclude interesting *CP*-violating new physics (NP) effects in other *B* decays. Since the decay $B \to J/\psi K_S$ ($b \to c\bar{c}s$) is a tree level process in the SM, the NP contributions to its amplitude are naturally suppressed. However, at loop level NP may give large contributions to the B^0-$\bar{B}^0$ mixing as well as to the loop-induced decay amplitudes. The former effects are universal to all B^0 decay modes and therefore constrained to be less than 20% compared with the SM contribution [1]. On the other hand, the effects of new physics in the decay amplitudes are nonuniversal and can show up in the comparison of the *CP* asymmetries in different decay modes [3].

One of the most promising processes for NP searches widely considered in literature [3–6] is $B \to \phi K_S$. In the SM the decay $b \to s\bar{s}s$ is a one-loop effect and, according to the KM mechanism, the *CP* asymmetry in $B \to \phi K_S$ decay measures with high accuracy the same quantity as $B \to J/\psi K_S$, namely, $\sin 2\beta$. The uncertainty for those processes in the SM is estimated to be [3,7]

$$|\phi(B \to J/\psi K_S) - \phi(B \to \phi K_S)| \lesssim \mathcal{O}(\lambda^2), \qquad (2)$$

where ϕ is the measured *CP* angle and $\lambda \approx 0.2$. Surprisingly, both *BABAR* [8] and Belle [9] obtain a negative value for the *CP* asymmetry in this decay mode. Their average result is

$$\sin 2\phi_{\phi K_S} = -0.39 \pm 0.41, \qquad (3)$$

where $\phi_{\phi K_S} \equiv \phi(B \to \phi K_S)$ denotes the measured *CP* angle. Despite large statistical errors those measurements establish a 2.7σ deviation from the SM prediction $\sin 2\phi_{\phi K_S} = \sin 2\beta_{J/\psi K}$ and may indicate an effect of new physics. Since the deviation of Eq. (3) from Eq. (1) is very large, first analyses [1,10–12] of this experimental result imply that one needs strongly enhanced gluonic penguin contributions to the decay amplitude as in the generic supersymmetric models, nonstandard flavor changing *Z*-boson couplings, supersymmetry without *R* parity, etc. to account for such a large deviation.

In this Letter we would like to clarify that the result Eq. (3) can actually be explained in a wide class of rather ordinary models from the flavor point of view: by the left-right symmetric models (LRSM) based on the gauge group $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ [13]. Those models predict the existence of a new charged gauge boson W_2 with a mass $M_2 \gtrsim 1.6$ TeV [14] which may mix with the SM gauge boson W_1 by the mixing angle $\xi \lesssim 0.013$ [15]. Because of the imposed discrete left-right symmetry the left- and right-handed Cabibbo-Kobayashi-Maskawa (CKM) matrices V_L and V_R, respectively, are related as $|V_L| = |V_R|$. However, their phases may differ from each other as happens in the models with spontaneous *CP* breaking [16–19] which has six phases in V_R. While the NP contribution to the B^0-$\bar{B}^0$ mixing is suppressed by the heavy scale M_2 in this model, the gluonic penguin contributions to the flavor changing decay $b \to s\bar{s}s$, which are proportional to the mixing angle ξ, are enhanced by a large factor m_t/m_b due to the presence of $(V + A)$ interactions in the loop, and by another factor of 4 due to the larger values of Inami-Lim–type loop functions. Together those enhancement factors may overcome the suppression by ξ, and the *CP* asymmetries in $B \to J/\psi K_S$ and $B \to K_S \phi$ may differ from each other by order unity due to the additional two independent phases in the $B \to K_S \phi$ decay amplitude. This scenario has important consequences on the *CP* asymmetries in $b \to s\bar{s}s$ dominated B_s decays such as $B_s \to \phi\phi$ which are predicted to be vanishing in the SM. In the LRSM the *BABAR* and Belle result Eq. (3) implies also the measurable *CP* asymmetries in B_s decays at Tevatron and the LHC. The low-scale scenario also has a potential to be tested directly at lepton [20] and hadron [21] colliders.

CP violation in B^0 decays takes place due to the interference between mixing and decay. The corresponding CP asymmetry depends on the parameter λ defined as [22]

$$\lambda = \left(\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}\right)\frac{\bar{A}}{A} = \frac{q}{p}\frac{\bar{A}}{A}, \tag{4}$$

where A and $\bar{A}$ are the amplitudes of B^0 and $\bar{B}^0$ decay to a common CP eigenstate, respectively. With a good accuracy $|q/p| = 1$ and the B-$\bar{B}$ mixing phase is given by $q/p = e^{-2i\phi_M}$. Neglecting the direct CP asymmetry one has $|\lambda| = 1$ and $\bar{A}/A = e^{-2i\phi_D}$ gives the phase in the decay amplitude. In this case the time-dependent CP asymmetry takes a particularly simple form

$$a_{CP}(t) = -\mathrm{Im}\lambda \sin(\Delta M t) = \sin 2(\phi_M + \phi_D)\sin(\Delta M t), \tag{5}$$

where ΔM is the mass difference between the two physical states. From Eqs. (4) and (5) it is clear that any new physics effect in the mixing will translate into $\phi_M \to \phi_M + \delta_M$ and will be universal to all decays while the effect in the decay, $\phi_D \to \phi_D + \delta_D$, will depend on the decay mode. As the NP in ϕ_M is already constrained to be below 20%, we proceed with studying the NP in decay amplitudes and comment on ϕ_M effects later.

The charged current Lagrangian in the LRSM is given by

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\bar{u}(\cos\xi V_L\gamma^\mu P_L - e^{i\omega}\sin\xi V_R\gamma^\mu P_R)dW_{1\mu} + \frac{g}{\sqrt{2}}\bar{u}(e^{-i\omega}\sin\xi V_L\gamma^\mu P_L + \cos\xi V_R\gamma^\mu P_R)dW_{2\mu} + \mathrm{H.c.}, \tag{6}$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$, W_1, W_2 are the charged vector boson fields with the masses M_1, M_2, respectively, ξ denotes their mixing, and ω is a CP phase.

The flavor changing decay $b \to s\bar{s}s$ is induced by the QCD, electroweak, and magnetic penguins. The dominant contribution comes from the QCD penguins with top quark in the loop. It is also known [23] that the electroweak penguins decrease the decay rate by about 30%. We shall add all those contributions to the QCD improved effective Hamiltonian. We start with the effective Hamiltonian due to the gluon exchange describing the decay $b \to s\bar{s}s$ at the scale M_1

$$H_{\mathrm{eff}}^0 = -\frac{G_F}{\sqrt{2}}\frac{\alpha_s}{\pi}V_L^{ts*}V_L^{tb}(\bar{s}[\Gamma_\mu^{LL} + \Gamma_\mu^{LR}]T^a b)(\bar{s}\gamma^\mu T^a s),$$

where

$$\begin{aligned}\Gamma_\mu^{LL} &= E_0(x)\gamma_\mu P_L + 2i\frac{m_b}{q^2}E_0'(x)\sigma_{\mu\nu}q^\nu P_R,\\ \Gamma_\mu^{LR} &= 2i\frac{m_b}{q^2}\tilde{E}_0'(x)[A^{tb}\sigma_{\mu\nu}q^\nu P_R + A^{ts*}\sigma_{\mu\nu}q^\nu P_L],\end{aligned} \tag{7}$$

the Γ_μ^{LR} term describes the new dominant left-right contribution due to the mixing angle ξ, and

$$\begin{aligned}A^{tb} &= \xi\frac{m_t}{m_b}\frac{V_R^{tb}}{V_L^{tb}}e^{i\omega} \equiv \xi\frac{m_t}{m_b}e^{i\sigma_1},\\ A^{ts} &= \xi\frac{m_t}{m_b}\frac{V_R^{ts}}{V_L^{ts}}e^{i\omega} \equiv \xi\frac{m_t}{m_b}e^{i\sigma_2}.\end{aligned} \tag{8}$$

Note that the phases $\sigma_{1,2}$ are independent and can take any value in the range $(0, 2\pi)$. The functions $E_0(x)$, $E_0'(x)$, and $\tilde{E}_0'(x)$ are Inami-Lim–type functions [24] of $x = m_t^2/M_1^2$ and are given in Ref. [19]. Notice that $\tilde{E}_0'(x_t)$ is numerically about a factor of 4 larger than the SM function $E_0'(x_t)$. Together with the m_t/m_b enhancement in A^{tb}, A^{ts} this practically overcomes the left-right suppression by small ξ and allows large CP effects in the decay amplitude due to the new phases $\sigma_{1,2}$. We note that the analogous effect is also responsible for the enhancement of gluonic penguins in general supersymmetric models [6].

To calculate B meson decay rates at the energy scale $\mu = m_b$ in the leading logarithm (LL) approximation we adopt the procedure from Ref. [24]. Using the operatorproduct expansion to integrate out the heavy fields, and to calculate the LL Wilson coefficients $C_i(\mu)$, we run them with the renormalization group equations from the scale of $\mu = W_1$ down to the scale $\mu = m_b$ (since the contributions of W_2 are negligible we start immediately from the W_1 scale). Because the new physics appears only in the magnetic dipole operators we can safely take over some well-known results from the SM studies. Therefore the LRSM effective Hamiltonian should include only these new terms which mix with the gluon and photon dipole operators under QCD renormalization. We work with the effective Hamiltonian

$$\begin{aligned}H_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}}\Bigg[&V_L^{us*}V_L^{ub}\sum_{i=1,2}C_i(\mu)O_i^u(\mu) + V_L^{cs*}V_L^{cb}\sum_{i=1,2}C_i(\mu)O_i^c(\mu)\\ &- V_L^{ts*}V_L^{tb}\left(\sum_{i=3}^{12}C_i(\mu)O_i(\mu) + C_7^\gamma(\mu)O_7^\gamma(\mu) + C_7^G(\mu)O_7^G(\mu)\right)\Bigg] + (C_iO_i \to C_i'O_i'),\end{aligned} \tag{9}$$

where $O_{1,2}$ are the standard current-current operators, O_3-O_6 and O_7-O_{10} are the standard QCD and electroweak penguin operators, respectively, and O_7^γ and O_8^G are the standard photonic and gluonic magnetic operators, respectively.

They can be found in the literature (e.g., Refs. [26,27]) and we do not present them here. The new operators to be added, $O_{11,12}$, are analogous to the current-current operators $O_{1,2}$ but with different chiral structure [25]. Because of the left-right symmetry the operator basis is doubled by including operators O_i' which can be obtained from O_i by the replacements $P_L \leftrightarrow P_R$.

Because the new physics affects only the Wilson coefficients C_7^γ, C_8^G, and C_7^γ, C_8^G is sufficient to consider the basis O_{1-6}, O_7^γ, O_8^G, and $O_{11,12} + (O \to O')$ for calculating them in the LL precision. The relevant matching conditions can be found in [19] and we do not present them here. The 20×20 anomalous dimension matrix decomposes into two identical 10×10 submatrices. The SM 8×8 submatrix of the latter one can be found in Ref. [27] and the rest of the entries have been calculated in Ref. [24]. In the LL approximation the low energy Wilson coefficients for five flavors are given by

$$C_i(\mu = m_b) = \sum_{k,l} (S^{-1})_{ik}(\eta^{3\lambda_k/46}) S_{kl} C_l(M_1), \tag{10}$$

where the λ_k's in the exponent of $\eta = \alpha_s(M_1)/\alpha_s(m_b)$ are the eigenvalues of the anomalous dimension matrix over $g^2/16\pi^2$ and the matrix S contains the corresponding eigenvectors. The result for the gluonic magnetic coefficients relevant for our studies is [5]

$$C_8^G(m_b) = \eta^{(14/23)}[E_0'(x) + A^{tb}\tilde{E}_0'(x)] + \sum_{i=1}^{5} h_i' \eta^{p_i'}, \tag{11}$$

$$C_8'^G(m_b) = \eta^{(14/23)} A^{ts*} \tilde{E}_0'(x), \tag{12}$$

where $h_i' = (0.8623, -0.9135, 0.0209, 0.0873, -0.0571)$ and $p_i' = (14/23, 0.4086, 0.1456, -0.4230, -0.8994)$. Using $\Lambda_{\overline{MS}}^{(5)} = 225$ MeV and $\mu = \bar{m}_b(m_b) = 4.4$ GeV we find numerically $C_7^\gamma = -0.331 - 0.523A^{tb}$, $C_7'^\gamma = -0.523A^{ts*}$, $C_8^G = -0.156 - 0.231A^{tb}$, and $C_8'^G = -0.231A^{ts*}$.

To calculate the hadronic matrix element $\langle O \rangle \equiv \langle K_S \phi | O | B \rangle$ for the $B \to K_S \phi$ decay amplitude we use the factorization approximation which has been extensively discussed in the literature [26,27,29] and we do not repeat it here. However, treating the most relevant matrix element for our studies,

$$\langle O_8^G \rangle = -\frac{2\alpha_s}{\pi}\frac{m_b}{q^2}\langle (\bar{s}_\alpha i\sigma_{\mu\nu}q^\mu P_R T^a_{\alpha\beta} b_\beta)(\bar{s}_\gamma \gamma^\nu T^a_{\gamma\delta} s_\delta)\rangle,$$

where q^μ is the momentum transferred by the gluon to the $(\bar{s}, s)$ pair, is nontrivial. Following [25] the result is [19]

$$\langle O_8^G \rangle = -\frac{\alpha_s}{4\pi}\frac{m_b}{\sqrt{\langle q^2 \rangle}}\left[\langle O_4 \rangle + \langle O_6 \rangle - \frac{1}{N_c}(\langle O_3 \rangle + \langle O_5 \rangle)\right],$$

and similarly for $\langle O_8'^G \rangle$. The parameter $\langle q^2 \rangle$ introduces certain uncertainty into the calculation. In the literature its value is varied in the range $1/4 \lesssim \langle q^2 \rangle / m_b^2 \lesssim 1/2$ [30].

In the factorization approach the amplitude $A \equiv \langle H_{\rm eff} \rangle$ of the decay $B \to \phi K_S$ takes a form [27]

$$A(B \to \phi K_S) = -\frac{G_F}{\sqrt{2}} V_L^{tb} V_L^{ts*} \times 2\left[a_3 + a_4 + a_5 - \frac{1}{2}(a_7 + a_9 + a_{10})\right] \times X^{(BK,\phi)}, \tag{13}$$

where $X^{(BK,\phi)}$ stands for the factorizable hadronic matrix element whose exact form is irrelevant for us since it cancels out in CP asymmetries. The coefficients a_i are given by

$$a_{2i-1} = C_{2i-1}^{\rm eff} + \frac{1}{N_c} C_{2i}^{\rm eff}, \qquad a_{2i} = C_{2i}^{\rm eff} + \frac{1}{N_c} C_{2i-1}^{\rm eff},$$

where the QCD improved coefficients $C_i^{\rm eff}$ can be found in [19]. Using $\sqrt{\langle q^2 \rangle} = m_b/\sqrt{2}$, $\xi = 0.01$, and $m_t/m_b = 60$ we obtain for the LL QCD improved amplitude

$$A(B \to \phi K_S) = -\frac{G_F}{\sqrt{2}} V_L^{tb} V_L^{ts*} \times 2[-0.016 + 0.0035(e^{i\sigma_1} + e^{-i\sigma_2})] \times X^{(BK,\phi)}. \tag{14}$$

The maximum effect occurs for phases $\sigma_1 = -\sigma_2 = \pi/2 + \delta_D$. Numerically we get $(\bar{A}/A)_{\max} = e^{\pm 0.91 i}$. We recall that this estimate is obtained for the most conservative $\langle q^2 \rangle$. Using more optimistic $\sqrt{\langle q^2 \rangle} = m_b/2$ the NP effect is increased to $(\bar{A}/A)_{\max} = e^{\pm 1.3 i}$. According to Eqs. (4) and (5) the NP phase in $\bar{A}/A$ can change the CP asymmetry by order unity. Therefore, consistency with the *BABAR* and Belle result Eq. (3) can be obtained in the LRSM.

Our explanation to the *BABAR* and Belle measurements of the time-dependent CP asymmetry in $B \to \phi K_S$ decays due to the NP in the decay amplitude has important consequences for the B_s decays to be measured at Tevatron and the LHC. One of the cleanest processes is the pure penguin induced decay $B_s \to \phi\phi$ ($b \to s\bar{s}s$). Its branching ratio is large, of the order of $B(B_s \to \phi\phi) \sim \mathcal{O}(10^{-5})$ [27], and the pollution from other SM diagrams is estimated to be of the order of $\mathcal{O}(1)\%$ [3]. Since the CP asymmetries in this mode should vanish in the SM, the decay $B_s \to \phi\phi$ should provide very sensitive tests of the SM at hadron machines.

Formally the $B_s \to \phi\phi$ amplitude is also given by Eq. (13) but with a proper hadronic matrix element $X^{(B_s\phi,\phi)}$. However, in the factorization approximation the hadronic matrix elements of the operators O_i and O_i' depend on the spin of the decay products. For $B_s \to PP$, VV where P and V denote any pseudoscalar and vector meson, respectively, one has $\langle O_i \rangle = -\langle O_i' \rangle$, while for the decays of the type $B_s \to PV$ one has $\langle O_i \rangle = \langle O_i' \rangle$. Therefore the magnetic penguin contributions which give NP effects may have different signs in different processes. Using the same numerical input as before we obtain

$$A(B_s \to \phi\phi) = -\frac{G_F}{\sqrt{2}} V_L^{tb} V_L^{ts*} \times 2[-0.016 + 0.0035(e^{i\sigma_1} - e^{-i\sigma_2})] \times X^{(B_s\phi,\phi)}. \quad (15)$$

Unless $\sigma_1 = -\sigma_2$, $\mathcal{O}(1)$ deviation from the SM prediction $a_{CP}^{\rm SM}(B_s \to \phi\phi) = 0$ can be expected with the maximal results $(\bar{A}/A)_{\rm max} = e^{\pm 0.91i(\pm 1.3i)}$ as before. Should $\sigma_1 = -\sigma_2$ indeed be the case, one has to search for the CP asymmetries in the processes $B_s^0 \to \eta\rho^0$, $B_s^0 \to \pi\phi$ which are PV type but may have large tree level contributions. However, this is unjustified fine-tuning and NP effects of the order of $\mathcal{O}(1)$ can be expected in both $B \to K_S\phi$ and $B_s \to \phi\phi$. Therefore Tevatron or LHC should be able to test our scenario also in B_s decays.

In conclusion, if the measured discrepancy between the time-dependent CP asymmetries in $B \to J/\psi K_S$ and $B \to \phi K_S$ decays is due to new physics, it can be explained, consistently with all experimental bounds, by the enhanced gluonic penguin contribution to the $B \to \phi K_S$ decay amplitude in the LRSM. This scenario implies also large CP asymmetry in the decay $B_s \to \phi\phi$ (and also in $B_s^0 \to \eta\rho^0$, $B_s^0 \to \pi\phi$) which can be tested in upcoming Tevatron and LHC.

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