CP Violation in a two-Higgs doublet model for the top quark: $B \rightarrow \psi K_S$

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Abstract

We explore charged-Higgs CP-violating effects in an intriguing two-Higgs doublet model which accords special status to the top quark. In this model the heaviness of the top quark originates naturally from the much larger VEV of the second Higgs doublet compared to that of the first. The phenomenology of this model is quite distinct from that of the usual formulations of the two-Higgs doublet model. In particular, the model can easily account for the observed CP violation in the kaon sector even if the CKM matrix is real. The associated non-standard CP phase can be monitored through measurements of the time-dependent CP asymmetry in $B \rightarrow \psi K_S$ in experiments at the upcoming B-factories.

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Despite the stunning successes of the Standard Model (SM) it is widely believed that it cannot be the complete theory. It is quite possible that the extraordinary mass scale of the top quark is giving us a hint as to the nature of the physics beyond the SM. In this note we pursue this theme within the context of an atypical two-Higgs doublet model (2HDM) which gives the top quark a special status. The gigantic mass scale of the top quark arises naturally in this extension of the SM since the top is the only fermion receiving its mass from the vacuum expectation value (VEV) of the second Higgs doublet. All the other fermions receive their masses (mostly) from the VEV of the first Higgs doublet. Besides providing a natural explanation for the largeness of \( m_t \), the introduction of the second Higgs doublet has an important bonus in that it allows a new source of CP violation: the charged Higgs sector of the model contains a CP-violating phase ("\( \delta \)") in addition to the usual Cabibbo-Kobayashi-Maskawa (CKM) phase \( \beta \) of the SM. This phase may play a useful role in baryogenesis since the CKM phase is believed not to be able to account for the baryon asymmetry of the universe in such calculations. Perhaps the most exciting feature of the new phase \( \delta \) is that it can be monitored in experiments at the upcoming \( B \) factories through time-dependent CP studies of \( B \rightarrow \psi K_S \).

The specific model which we consider was introduced in Ref. [3] and is essentially a special case of the 2HDM of type III (i.e., Model III) [4]. We regard this model as an effective low-energy theory in which only the (slightly extended) Higgs sector and the regular SM particles remain as relevant dynamical particles. The above-mentioned ansatz regarding the quark masses leads to a very specific pattern of flavour- and (in general) CP-violating couplings. In particular, this model exhibits tree-level flavour-changing neutral Higgs interactions, but only in the up-type quark sector. It was shown in Ref. [3] that this model can have significant effects on the electron electric dipole moment and on \( D-\bar{D} \) mixing.

The main purpose of this work is to point out that this top-two-Higgs-doublet model (T2HDM) can give rise to a very significant amount of non-standard CP violation in charged Higgs interactions [5]. Contrary to conventional wisdom, perhaps, these non-standard inter-
actions are not particularly well-constrained by flavour-changing neutral current processes. For the physics of interest to this work the important unknown parameters of the model are \( \tan \beta \) (i.e., \( v_2/v_1 \)), \( m_H \) and \( \delta \). We have delineated the allowed parameter space of the model by considering the repercussions for \( K \) and \( B \) decays and for \( K-\overline{K} \) and \( B-\overline{B} \) mixing. Since the parameter space is relatively large, we have chosen to focus on three “case studies.” In the first we take the SM CKM phase \( \gamma \) to be identically zero. This scenario is particularly interesting since the CP-violating phase \( \delta \) in the Higgs sector of the theory is then entirely responsible for the CP violation observed in the kaon system. In the second case study we set \( \gamma \) equal to \( 68^\circ \), which is the central value of the SM fits (i.e., \( \gamma = 68^\circ \pm 15^\circ \)). For the third case, \( \gamma \) is taken to be negative and equal to \(-45^\circ \). The important point is that, in general, the CP asymmetry for \( B \to \psi K_S \) in this model is appreciably different from the value expected within the context of the SM. One feature which distinguishes the present analysis from many previous studies of non-standard effects in \( B \to \psi K_S \) is that in the present case the effect comes from the new CP-violating phase in the \( B \) and \( \overline{B} \) decay amplitudes, not from a new phase in \( B-\overline{B} \) mixing.

Let us briefly recapitulate some important features of the model of Ref. [3]. Consider the following Yukawa Lagrangian:

\[
L_Y = -\overline{L}_L \phi_1 E \ell_R - \overline{Q}_L \phi_1 F d_R - \overline{Q}_L \phi_2 G^{(1)} u_R - \overline{Q}_L \phi_2 G^{(2)} u_R + h.c.,
\]

where \( \phi_i = i \sigma^2 \phi_i^* \) (\( i = 1, 2 \)), and where \( E, F \) and \( G \) are \( 3 \times 3 \) matrices in generation space; \( 1^{(1)} \equiv \text{diag}(1, 1, 0); 1^{(2)} \equiv \text{diag}(0, 0, 1); \) and \( Q_L \) and \( L_L \) are the usual left-handed quark and lepton doublets. This Lagrangian gives special status to the top quark, as evidenced by the fact that only \( \phi_2 \) (and not \( \phi_1 \)) couples to \( t_R \). Let us set the VEVs of \( \phi_1 \) and \( \phi_2 \) to be \( v_1/\sqrt{2} \) and \( v_2 e^{i \sigma}/\sqrt{2} \), respectively. In keeping with the spirit of this model, we require that \( \tan \beta = v_2/v_1 \) be relatively large (say at least of order twenty).

The expression for the quark-charged-Higgs Lagrangian takes the form:

\[
L_Y^C = (g/\sqrt{2}m_W) \left\{ -\overline{u}_L V m_d d_R \left[ G^+ - \tan \beta H^+ \right] + \overline{u}_R m_u V d_L \left[ G^+ - \tan \beta H^+ \right] + \overline{u}_R \Sigma^1 V d_L \left[ \tan \beta + \cot \beta \right] H^+ + h.c. \right\},
\]
where $G^\pm$ and $H^\pm$ represent the would-be Goldstone bosons and the physical charged Higgs bosons, respectively. Here $m_u$ and $m_d$ are the diagonal up- and down-type mass matrices, $V$ is the usual CKM matrix and $\Sigma \equiv m_u U_R^1 1^{(2)} U_R$. $U_R^1$ is the unitary matrix which diagonalizes the right-handed up-type quarks. Since $\Sigma$ is in general not a diagonal matrix, the last term in Eq. (2) can give rise to unusual couplings that can violate CP in non-standard ways. To see this, let us write the unitary matrix $U_R$ in a form similar to that used in Ref. [3]:

$$U_R = \begin{pmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \sqrt{1 - |\epsilon_{ct} \xi|^2} \\ \epsilon_{ct} \xi \sqrt{1 - |\epsilon_{ct} \xi|^2} \end{pmatrix}, \quad (3)$$

where $\epsilon_{ct} \equiv m_c/m_t$ and where $\xi$ is a complex number of order unity [9]. Inserting $U_R$ into the definition of $\Sigma$, we obtain

$$\Sigma = \begin{pmatrix} 0 & 0 & m_c \epsilon_{ct} \xi^* \sqrt{1 - |\epsilon_{ct} \xi|^2} \\ 0 & m_c \epsilon_{ct} \xi \sqrt{1 - |\epsilon_{ct} \xi|^2} & m_t (1 - |\epsilon_{ct} \xi|^2) \end{pmatrix}. \quad (4)$$

It is clear from this expression that this model generically has a rather large non-standard $b\rightarrow c\rightarrow H$ vertex. This can lead to significant CP violation effects in $B \rightarrow \psi K_S$. Consider, in particular, the time-dependent CP-asymmetry $a(t) \equiv \left[ \Gamma(B(t)) - \Gamma(\bar{B}(t)) \right] / \left[ \Gamma(B(t)) + \Gamma(\bar{B}(t)) \right]$, for $B \rightarrow \psi K_S$. In the SM $a(t)$ is free of hadronic uncertainties and is given by $a_{SM}(t) = -\sin(2\beta_{CKM}) \sin(\Delta M t)$ [3], where $\Delta M = M_{B_{H}} - M_{B_{L}}$ is the mass difference between the neutral $B$ mesons and $\beta_{CKM} \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$. Existing experimental information seems to constrain $\beta_{CKM}$ quite tightly: $\sin(2\beta_{CKM}) = 0.75 \pm 0.10$ [3]. The asymmetry $a(t)$ is a very clean way to measure the CKM angle $\beta_{CKM}$ and thereby provides an important test of the SM [4].

CP-odd effects due to new physics can affect the asymmetry $a(t)$ in several qualitatively different ways. The most direct effect comes about if we allow the new interactions to be partly (or fully) responsible for the observed CP violation in the kaon system. In this case $\beta_{CKM}$ itself can be different from the value expected within the context of the SM, and can even be zero or negative. For a given value of $\beta_{CKM}$ there can also be new contributions to $a(t)$ arising from $B-\bar{B}$ mixing and from CP violation in the $B$ and $\bar{B}$ decay amplitudes.
themselves. The $B$-$\overline{B}$ mixing effect, being suppressed either by $1/\tan^4 \beta$ for large $\tan \beta$ or by $m_b^2/m_H^2$, is generically quite small in this model and may safely be ignored. By way of contrast, CP violation in the amplitudes can in principle be appreciable in this model, leading to a sizable correction to the asymmetry $a(t)$ compared to the value expected within the SM. Ignoring perturbative QCD effects, there are two tree-level diagrams which contribute to $B \to \psi K_S$: the SM $W$-mediated diagram and the new charged-Higgs-mediated diagram. The effective Lagrangian is then well-approximated by

$$L_{\text{eff}} \simeq -2\sqrt{2} G_F V_{cb} V_{cs}^* \left[ \overline{c}_L \gamma_\mu b_L \overline{s}_L \gamma^\mu c_L + 2\zeta e^{i\delta} \overline{c}_R b_L \overline{s}_L c_R \right] + \text{h.c.},$$

(5)

where $\zeta e^{i\delta} \equiv (1/2) (V_{tb}/V_{cb}) (m_c \tan \beta/m_H)^2 \xi^*$ with $\zeta$ taken to be real and positive. In writing the above expression, we have neglected terms which are subdominant for $\tan \beta \gg 1$ and $|\xi| = O(1)$. Note that the Higgs-mediated contribution can in principle be large since it is proportional to $V_{tb}/V_{cb} \sim 25$ as well as to $\tan^2 \beta$ [11].

Using Fierz identities and assuming factorization, we may write the total amplitude for $B \to \psi K_S$ as $A \equiv A(B \to \psi K_S) \simeq A_{\text{SM}} \left[ 1 - \zeta e^{-i\delta} \right]$. To the extent that factorization holds, there is no relative strong phase between the $W$- and charged-Higgs-mediated diagrams, so that the $B$ and $\overline{B}$ decay amplitudes have the same magnitude and differ only by a CP-violating phase. We may thus write $A/\overline{A} = (A_{\text{SM}}/A_{\text{SM}}) \exp(-2i\vartheta)$, where $\vartheta$ represents the correction to $\beta_{\text{CKM}}$ due to the Higgs-mediated contribution to $B \to \psi K_S$; i.e., the time-dependent asymmetry $a(t)$ now measures $\beta_{\text{CKM}} + \vartheta$ instead of $\beta_{\text{CKM}}$. The angle $\vartheta$ is simply given by $\tan \vartheta = \zeta \sin \delta/(1 - \zeta \cos \delta)$ and can, in principle, be rather large.

Let us discuss some of the experimental constraints on $\vartheta$. The most stringent experimental constraints on the parameter space of the T2HDM come from $b \to s\gamma$ and $K$-$\overline{K}$ mixing. $b \to s\gamma$ places an important constraint on the parameter space of the T2HDM just as it does for Model II, where a $\tan \beta$-independent lower bound of approximately 370 GeV may be placed on the charged Higgs mass [12]. The situation in the present case is somewhat complicated by the fact that the Higgs contribution in this model has a CP-violating phase. This extra degree of freedom means that the new contribution to $b \to s\gamma$ is complex and
need not interfere constructively with the SM contribution at LO, as is the case in Model II. As a result, the shape of the excluded region in the $\tan \beta$-$m_H$ plane is strongly dependent on the CP-violating phase $\delta$.

In order to minimize the theoretical uncertainties associated with $b \to s\gamma$, it is customary to consider the ratio $R = \mathcal{B}(b \to X_s\gamma)/\mathcal{B}(b \to X_c\ell\nu)$. The branching ratio appearing in the numerator of this expression has been investigated by both the CLEO II and ALEPH collaborations [13]. The experimental results may be combined to obtain the weighted average $R^{\text{exp}} = (2.90 \pm 0.46) \times 10^{-3}$. Considerable progress has also been made on the theoretical side of this decay in recent years. In particular, complete NLO QCD corrections [14] as well as some two-loop electroweak corrections [15] have now been incorporated into the calculation of $R$ within the context of the SM [16].

The T2HDM can affect the ratio $R$ through diagrams similar to the usual SM diagrams [17] in which the $W$ boson is replaced by a charged Higgs. The Higgs contribution gives a correction to the matching condition for the LO Wilson coefficient $C_7^{(0)}$ at the scale $m_W$ so that the relevant effective Wilson coefficient at the scale $\mu \sim \mathcal{O}(m_b)$ is modified according to $C_7^{(0)}(\mu) \to C_7^{(0)}(\mu) + (\alpha_s(m_W)/\alpha_s(\mu))^{16/23} \delta C_7^{(0)}(m_W)$, where

$$
\delta C_7^{(0)}(m_W) = \sum_{u=c,t} \kappa_u \left[ -\tan^2 \beta + \left( \Sigma^T V^* \right)_{us} \left( \tan^2 \beta + 1 \right) / m_u V^*_{us} \right] \\
\times \left\{ B(y_u) + A(y_u) \left[ -1 + \left( \Sigma^T V \right)_{ub} \left( \cot^2 \beta + 1 \right) / m_u V_{ub} \right] / 6 \right\}.
$$

In this expression $\kappa_u = \pm 1$ for $u = c,t$; $y_u = (m_u/m_H)^2$; and $A$ and $B$ are standard expressions [18,19].

In order to compare our theoretical calculation of $R^{\text{theory}}$ with the experimental number quoted above, we assign a theoretical uncertainty of $\delta R^{\text{theory}} = 0.7 \times 10^{-3}$ to $R^{\text{theory}}$ [12]. This uncertainty corresponds roughly to the variation of $R^{\text{theory}}$ as $\mu$ is varied between $m_b/2$ and $2m_b$. Adding the experimental and theoretical uncertainties in quadrature, we find the following constraint on $R^{\text{theory}}$: $0.0012 \leq R^{\text{theory}} \leq 0.0046$.

We next consider the implications of the T2HDM for $K-\overline{K}$ mixing. The total short distance contribution to $\Delta m_K$ is given by
\[(\Delta m_K)_{SD} = (G_F^2/6\pi^2)f_K^2 B_K m_K \lambda_c^2 \times \left[ m_c^2 \eta_1 + (m_c^4 \tan^4 \beta/4m_H^2)\eta_1' \right] \] (7)

where the first term is the usual SM contribution and the second term is the dominant contribution in the T2HDM due to the \(HHcc\) box diagram. Here \(B_K\) is the usual bag factor, \(\lambda_c = V_{cs} V^{*}_{cd}\), and \(\eta_1\) and \(\eta_1'\) are the QCD corrections to the two box diagrams. The SM top quark contribution is a few percent of the charm quark contribution and is not included here. Similarly, the contributions from \(WHcc\) and other box diagrams are negligible in the large \(\tan \beta\) limit and are ignored.

In order to numerically deduce the allowed parameter space subject to the \(\Delta m_K\) constraint we use the method described in [7]. Assuming the magnitude of the long distance contribution to \(\Delta m_K\) to be no larger than 30\%, we find the 95\% C.L. limit \(m_H/\tan^2 \beta > 0.48\) GeV for \(\tan \beta > 10\) [20]. Note that the \(\tan^4 \beta\) enhancement in \(\Delta m_K\) generally leads to a very severe lower bound on the Higgs mass for large \(\tan \beta\) – this is a unique feature of the T2HDM.

Due to the \(\tan^4 \beta\) dependence, the \(CP\)-violating parameter \(\epsilon_K\) also receives its largest correction from the \(HHcc\) box diagram in the large \(\tan \beta\) limit. The SM contribution is well known [21]. The dominant Higgs contribution is given by

\[\epsilon_K^H = e^{i\pi} C e_B A \lambda^4 \eta_1' \sqrt{\rho^2 + \eta^2} \sin(\gamma + \delta)|\xi|(m_c \tan \beta)^4/4m_W^2 m_H^2\] (8)

where \(A, \lambda, \rho,\) and \(\eta\) are the CKM parameters in the Wolfenstein parameterization [22], \(\gamma \equiv \tan^{-1} \eta/\rho\) is the CKM phase [3], and \(C_e = G_F^2 f_K^2 m_W^2 m_K/6\sqrt{2}\pi^2 \Delta m_K = 3.78 \times 10^4\).

Since \(\gamma\) is essentially a free parameter in this model [23], we can obtain bounds on the parameter \(Y \equiv \sin(\gamma + \delta)|\xi|(\tan \beta/20)^4(200 \text{ GeV}/m_H)^2\) for any given value of \(\gamma\) by allowing \(\sqrt{\rho^2 + \eta^2}\) to vary within its 1\% uncertainties derived from \(b \rightarrow u e \nu\). (We also allow \(A, \eta_1',\) etc. to vary, as above.) For \(\gamma = 0^\circ\) we obtain the 95\% C.L bound \(0.08 < Y < 0.39\); the bound becomes \(0.14 < Y < 0.65\) for \(\gamma = -45^\circ\). If we assume that \(\gamma\) takes its SM central value of \(68^\circ\) [4], the bound becomes \(-0.085 < Y < 0.08\). Unlike the constraint on \((m_H, \tan \beta)\) coming from \(\Delta m_K\), the one coming from \(\epsilon_K\) depends on \(|\xi|\) and \(\delta\).
Figure 1 shows plots in the \( \tan \beta - m_H \) plane for a few representative values of the parameters of this model. In all of these plots we have fixed \( |\xi| \) to be unity, which is a natural choice in this model. The shaded bands in Fig. 1 correspond to the regions allowed by all three constraints. The amplitude of the time-dependent CP asymmetry in \( B \to \psi K_S \) is now given by \( a_{\psi K_S} \equiv \sin [2(\beta_{\text{CKM}} + \vartheta)] \). Contours of constant \( \vartheta \) have a very simple form in the \( \tan \beta - m_H \) plane: they are lines of constant slope emanating from the origin of that plane. We have suppressed such contours to avoid overcrowding the plots. Figure 2 shows the allowed values of \( \sin [2(\beta_{\text{CKM}} + \vartheta)] \) as a function of the CP-violating parameter \( \delta \). In order to clearly illustrate charged Higgs effects, we fix \( \sqrt{\rho^2 + \eta^2} = 0.41 \) (this is its central value \(^{[7]}\)) so that \( \beta_{\text{CKM}} \) is uniquely determined for a given \( \gamma \). This situation might well correspond to a future scenario in which measurements of \( b \to u e \nu \) have become more precise.

For illustration let us focus on three representative choices for \( \gamma \) (see Fig. 2). The first corresponds to a real CKM matrix; i.e., \( \gamma = 0^\circ \). In this case the phase \( \delta \) is solely responsible for the observed CP violation in the \( K - \bar{K} \) system. For a given \( \delta \), the upper limit of the allowed region corresponds to the intersection of the \( b \to s \gamma \) curve with the more stringent of the \( \Delta m_K \) and the \( \epsilon_K \) curves in the \( \tan \beta - m_H \) plane. The excluded regions for \( \delta \) come dominantly from the \( \epsilon_K \) constraint. It is interesting to note that small values (\( \sim 5^\circ \)) for \( \delta \) are not ruled out by \( \epsilon_K \) due to the \( \tan^4 \beta \) enhancement factor in Eq. \(^{[8]}\). This scenario gives a very clear signature: instead of measuring an asymmetry of order \( \sin 2\beta_{\text{CKM}} \sim 0.75 \) as expected in the SM, one would find an asymmetry no larger than about 0.27.

Figure 2 also shows the allowed range of the \( CP \) asymmetry \( a_{\psi K_S} \) for another phenomenologically interesting case, \( \gamma = 68^\circ \). It is evident from this plot that significant deviations from the pure SM value (i.e. the horizontal line corresponding to \( \vartheta = 0 \)) are possible in this scenario. Depending on the value of \( \delta \), the partial rate asymmetry in \( B \to \psi K_S \) can range between \( \sim 42\text{--}90\% \) and therefore may be appreciably different from the SM expectation of \( \sim 75\% \).

As the third scenario, we show in Fig. 2 how the \( CP \) asymmetry \( a_{\psi K_S} \) can even have
an opposite sign relative to the standard model expectation. This generally occurs when \( \gamma \) takes negative values which in turn gives a negative \( \beta_{\text{CKM}} \). As an example, the allowed region in the \( a_{\psi K_S} - \delta \) plane is shown for \( \gamma = -45^\circ \). This scenario gives a distinct signal for physics beyond the SM.

To summarize, we have presented a study of CP violation in a two-Higgs-doublet model that accords a special status to the top quark and accommodates the remarkable heaviness of the top quark rather naturally. While the model has repercussions for numerous experiments \[24\], we have focused here on its effects on the time-dependent CP asymmetry in \( B \rightarrow \psi K_S \). This asymmetry is of particular interest due to the fact that reliable theoretical predictions can be made here and also because intense experimental activity by the \( B \) factories is anticipated on this decay mode in the very near future. The asymmetry in this model can differ significantly from the predictions of the SM and can even change sign with respect to the SM expectation. These features may be helpful in leading to the discovery of new physics.

We thank D. Atwood, A. Czarnecki and O. Vives for helpful discussions and comments. This research was supported in part by the U.S. Department of Energy under contract numbers DE-AC02-98CH10886 and DE-FG02-91ER40681 (Task B). K.K. was also supported in part by the Natural Sciences and Engineering Research Council of Canada and by an SRTP grant at Taylor University. G.W. is grateful for the hospitality of the High Energy Theory Group at Brookhaven National Lab and of the Fermilab Theoretical Physics Department.
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[10] The subscript is added to $\beta_{\text{CKM}}$ to distinguish it from $\beta \equiv \tan^{-1}(v_2/v_1)$.

[11] Indeed this non-standard source may contribute $\sim 20\%$ to the observed branching ratio.
for $B \to \psi K_S$ which is much smaller than the intrinsic theoretical uncertainties in the absolute rate calculation.

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[20] We take all error distributions (both for the theoretical and the experimental quantities) to be rectangular, with widths $\pm 1\sigma$.

[21] G. Buchalla, et al., Rev. Mod. Phys. 68, 1125 (1996).

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[24] For example, the charged Higgs exchange contribution to the neutron EDM in this
A model can be as large as $10^{-27} - 10^{-26}$ e cm.
FIG. 1. Experimental constraints on the T2HDM from $b \to s\gamma$, $\epsilon_K$ and $\Delta m_K$. The allowed regions are shaded. The dots indicate where the largest values of $|\vartheta|$ occur: these are $\vartheta = 7.0^\circ$ and $\vartheta = 5.5^\circ$ in (a) and (b), respectively. The plot for $\gamma = -45^\circ$ is similar to that of $\gamma = 0^\circ$, and is not shown.
FIG. 2. Amplitude of the time-dependent CP asymmetry $a_{ψK_S} ≡ \sin(2β_{CKM} + 2θ)$ versus the non-standard CP-odd phase $δ$ for $B \to ψK_S$. The top horizontal line is for the SM assuming the best fit value ($\sin 2β_{CKM} = 0.75$) of Ref. [6]. The shaded regions correspond to the allowed ranges of the asymmetry in the T2HDM for three representative choices of $γ$: $γ = 68°$ is the best fit of Ref. [6], $γ = 0°$ corresponds to a real CKM matrix, and $γ = -45°$ changes the sign of $a_{ψK_S}$ relative to the SM expectation.