Explicit CP violation in the Dine-Seiberg-Thomas model

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The possibility of explicit CP violation is studied in a supersymmetric model proposed by Dine, Seiberg, and Thomas, with two effective dimension-five operators. The explicit CP violation may be triggered by complex phases in the coefficients for the dimension-five operators in the Higgs potential, and by a complex phase in the scalar top quark masses. Although the scenario of explicit CP violation is found to be inconsistent with the experimental data at LEP2 at the tree level, it may be possible at the one-loop level. For a reasonable parameter space, the masses of the neutral Higgs bosons and their couplings to a pair of Z bosons are consistent with the LEP2 data, at the one-loop level.

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1. \textbf{INTRODUCTION}

It is reasonable to assume that any phenomenological model should accommodate the violation of the CP symmetry as one of key features, since the CP violation has been observed in the neutral kaon system more than four decades ago [1] and it is one of the Sakharov conditions for the baryogenesis in cosmology to explain the baryon asymmetry of the universe [2]. The Standard Model (SM) may explain the small CP violation in the weak interactions in terms of a complex phase in the Cabibbo-Kobayashi-Maskawa matrix for the charged weak current [3]. However, the size of the complex phase in the SM is too small to satisfy the Sakharov conditions with respect to the baryon asymmetry.

As an alternative source of CP violation, Weinberg has noticed that if a model possesses at least two Higgs doublets, CP violation may occur in its Higgs sector through the mixing between the CP even and the CP odd states [4]. It is clear that the supersymmetric standard models satisfy the requirement that Weinberg has demanded, because they have at least two Higgs doublets in order to generate the masses for up-like quarks and down-like quarks independently [5-8].

Thus, a large number of articles have been devoted to investigate the possibility of CP violation in supersymmetric standard models. The minimal supersymmetric standard model (MSSM), the simplest version of supersymmetric standard models, has just two Higgs doublets. Therefore, in principle, the MSSM may accommodate CP violation by means of complex phases in its neutral Higgs sector. In practice, it has been found that CP violation is impossible to occur either explicitly or spontaneously in the Higgs sector of the MSSM at the tree level. If the $\mu$ parameter and the soft supersymmetry breaking parameters may possess complex phases, the redefinition of Higgs fields can always eliminate them. A global phase rotation can further eliminate any complex phases in the vacuum expectation values of two Higgs doublets. At the one-loop level, it has been studied that explicit CP violation is possible in the MSSM, but spontaneous CP violation scenario is difficult to be realized in the MSSM, because the mass of the lightest neutral Higgs boson in the scenario turns out to be very light to satisfy the LEP2 result for Higgs search [9-11].

Quite recently, a model has been proposed by Dine, Seiberg, and Thomas within the framework of the effective field theory analysis [12]. They have shown that the corrections from the new physics beyond the MSSM may be described in terms of higher-dimensional operators below the scale of the new physics. The simplest version, which we call the Dine-Seiberg-Thomas model (DSTM), has just two dimension-five operators with the MSSM particle content in its Higgs sector [13-16].

We have been attracted by the possibility that the DSTM may also accommodate CP violation in its Higgs sector. We have found that the DSTM may indeed allow spontaneous CP violation at the one-loop level, for wide ranges of parameters values, where top quark and scalar top quark loops are taken into account [17]. In the spontaneous CP violation scenario, the upper bound on the radiatively corrected mass of the lightest neutral Higgs boson in the DSTM is calculated to be 87 GeV. This value seems to be too small, but it does not contradict with the LEP2 data, as the relevant coupling coefficients are also small.

This article is the second part of our study on the DSTM within the context of CP violation. In this article, we study the possibility of explicit CP violation in the DSTM. In the DSTM, there are three possible sources of explicit CP violation, namely, the complex phases in the coefficients of two dimension-five operators and in the parameters of the MSSM sector.

We find that explicit CP violation scenario in the DSTM at the tree level is practically unacceptable, because the mass of the lightest neutral Higgs boson in the scenario is inconsistent with the LEP2 data. However, at the one-loop level, the radiative corrections from the top and scalar top quark loops allow the DSTM to accommodate explicit CP violation for a wide region in the
II. EXPLICIT CP VIOLATION AT TREE LEVEL

The Higgs potential at the tree level may be written as
\begin{equation}
V^0 = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 - \left( m_{ud}^2 H_u H_d + \text{H.c.} \right) + \frac{1}{8} (g^2 + g^2) \left( |H_u|^2 - |H_d|^2 \right)^2 + \left[ 2 \varepsilon_1 |H_d|^2 + |H_d|^2 H_u H_d \right] + \varepsilon_2 (H_u H_d)^2 + \text{H.c.} ,
\end{equation}

where $H_d^T = (H_0^d, H_d^0)$ and $H_u^T = (H_0^u, H_u^0)$ are two Higgs doublets, $g$ and $g$ are respectively the gauge coupling coefficients for $U(1)$ and $SU(2)$, $m_u$, $m_d$, and $m_{ud}$ are the mass parameters, and $\varepsilon_{1,2}$ are the coefficients for two effective dimension-five operators in the DSTM. These new coefficients represent the higher-dimensional interactions as quartic Higgs couplings.

There are several sources of complex phases in the tree-level Higgs potential: $\varepsilon_1$ and $\varepsilon_2$ may have complex phases $\varphi_1$ and $\varphi_2$, respectively; $m_{ud}$ may also be generally complex whereas $m_u$ and $m_d$ can be made real. However, the phase of $m_{ud}$ may be removed by redefining the phases of the two Higgs doublets. After redefinition of their phases, the Higgs doublets may be written as
\begin{equation}
H_d = \begin{pmatrix} v_d + \phi_d + i \psi_d \\ H_d^0 \end{pmatrix} , \quad H_u = \begin{pmatrix} H_u^T \\ v_u + \phi_u + i \psi_u \end{pmatrix} ,
\end{equation}

where $v_d$ and $v_u$ are the vacuum expectation values of the neutral Higgs fields. We assume that they are real. If CP symmetry is conserved in the Higgs sector, $\phi_d$ and $\phi_u$ would be the scalar fields while $\psi_d$ and $\psi_u$ would be the pseudoscalar fields, and a linear combination of the two pseudoscalar fields would be the pseudo-Goldstone mode.

There are two tadpole minimum conditions with respect to $\psi_d$ and $\psi_u$. If CP is conserved in the Higgs sector, the minimum conditions would be trivial. In our case of explicit CP violation, the minimum conditions are no longer trivial. However, the two minimum conditions yield a single identical equation. This equation gives us a relationship between complex phases at the tree level, in case of explicit CP violation, as
\begin{equation}
\sin \varphi_1 = - \frac{\varepsilon_2}{\varepsilon_1} \cos \beta \sin \beta \sin \varphi_2
\end{equation}

where $\tan \beta = v_u / v_d$ and $\varphi_i$ are the complex phases of $\varepsilon_i$. We may use this relationship to reduce the number of independent complex phases. Therefore, in the following expressions, $\varphi_1$ is not an independent variable but simply an expression depending on $\varepsilon_1$, $\tan \beta$, and $\varphi_2$.

The matrix elements of $M^0$, the symmetric $3 \times 3$ mass matrix for the neutral Higgs bosons at the tree level, are given explicitly as
\begin{equation}
M^0_{11} = m_Z^2 \cos^2 \beta + m_{ud}^2 \tan \beta + 2 \varepsilon_1 v^2 (1 + 2 \cos 2\beta) \tan \beta \cos \varphi_1 ,
M^0_{22} = m_Z^2 \sin^2 \beta + m_{ud}^2 \cot \beta + 2 \varepsilon_1 v^2 (1 - 2 \cos 2\beta) \cot \beta \cos \varphi_1 ,
M^0_{33} = \frac{|m_{ud}|^2}{\cos \beta \sin \beta} - 2 \varepsilon_1 v^2 \cos \varphi_1 ,
M^0_{12} = - m_Z^2 \sin \beta \cos \beta - m_{ud}^2 + 6 \varepsilon_1 v^2 \cos \varphi_1 ,
M^0_{13} = - 6 \varepsilon_1 v^2 \sin \beta \cos \phi_1 - \frac{1}{2} \varepsilon_2 v^2 (5 \sin \beta + \sin 3\beta) \sin \phi_2 ,
M^0_{23} = - 6 \varepsilon_1 v^2 \sin \beta \sin \phi_1 - \frac{1}{2} \varepsilon_2 v^2 (5 \cos \beta - \cos 3\beta) \sin \phi_2 ,
\end{equation}

where $v = \sqrt{v_u^2 + v_d^2} = 175 \text{ GeV}$ and $m_Z^2 = (g^2 + g^2) v^2 / 2$ is the squared mass of $Z$ boson.

Among them, the CP violation is triggered by $M_{13}$ and $M_{23}$, which mix the scalar and pseudoscalar Higgs fields. If $\varphi_1 = \varphi_2 = 0$, the CP symmetry would be conserved, and both $M_{13}$ and $M_{23}$ would be zero. In this case, $M^0_{33}$ would be the squared mass of the pseudoscalar Higgs boson of the DSTM, and the two eigenvalues of the upper-left $2 \times 2$ submatrix of $M^0$ would be the squared masses of two scalar Higgs bosons.

Note that, if $\varepsilon_1 = \varepsilon_2 = 0$, only the first term of $M^0_{33}$ remains, which is identical to the squared mass of the pseudoscalar Higgs boson at the tree level in the CP-conserving MSSM, $m_{h_s}^2 = |m_{ud}|^2 / \cos \beta \sin \beta$.

In the DSTM, they are not zero in general, and therefore the pseudoscalar Higgs boson in the DSTM has additional contributions from the dimension-five operators, the second and the third terms of $M^0_{33}$. These higher-dimensional contributions do not vanish even if $\varphi_1 = \varphi_2 = 0$, that is, in the CP-conserving limit. It should also be noticed that $\varphi_1$ and $\varphi_2$ are responsible for the scalar-pseudoscalar mixings at the tree level.

By diagonalizing $M^0$, three eigenvalues are calculated. They are sorted in increasing order in order to obtain three squared masses for the neutral Higgs bosons in the DSTM in the explicit CP violation scenario. The upper bound on the mass of the lightest neutral Higgs boson in the DSTM is obtained as
\begin{equation}
m_{h_1}^2 \leq m_Z^2 \cos^2 2\beta + 8 \varepsilon_1 v^2 \sin 2\beta \cos \varphi_1 + 2 \varepsilon_2 v^2 \sin^2 2\beta \cos \varphi_2 .
\end{equation}

Note that, if $\varepsilon_1$ and $\varepsilon_2$ are positive, the mass of the lightest neutral Higgs boson increases. On the other hand, in the CP-conserving DSTM, the mass of the pseudoscalar Higgs boson decreases if $\varepsilon_1$ and $\varepsilon_2$ are positive.
For the numerical analysis, we choose \( m_{A^0} \), the physical tree-level mass of the pseudoscalar Higgs boson in CP-conserving MSSM, instead of \( m_{ud} \) as a free parameter. The ranges for the free parameters are set as follows: 

\[ 2 < \tan \beta < 30, \quad |\xi_1| < 0.025, \quad |\xi_2| < 0.025, \quad |\varphi_2| < \pi/2, \quad \text{and} \quad 0 < m_{A^0} < 1000 \text{ GeV}. \]

We first calculate the tree-level masses of the three neutral Higgs bosons in the DSTM. We find that \( m_{h_1} \) may be as large as about 98 GeV within our parameter space. The allowed ranges for the masses of the other neutral Higgs bosons are 

\[ 15 < m_{h_2} < 1017 \text{ GeV} \quad \text{and} \quad 91 < m_{h_3} < 1017 \text{ GeV}. \]

Then, we calculate the coupling coefficients of the three neutral Higgs bosons to a pair of \( Z \) bosons, and normalize them with respect to the corresponding quantity in the SM. The normalized coupling coefficients are given by

\[ G_{ZZh_i} = \cos \beta O_{1i} + \sin \Omega_{2i}, \quad (6) \]

where \( O_{ij} \) are the elements of the orthogonal matrix that diagonalizes \( M^0 \).

In terms of these masses and the normalized \( Z Z h_i \) coupling coefficients, we examine the discovery limit of any one of the three neutral Higgs bosons in the DSTM with explicit CP violation, by comparing them with the experimental results for the Higgs search at LEP2 to all the Higgs couplings to a \( Z \) boson pair [18].

We find that at least one of the three neutral Higgs bosons has a very strong coupling to a pair of \( Z \) bosons, if its mass is less than 114.5 GeV. This implies that at least one of the three neutral Higgs bosons in the DSTM is above the discovery limit of LEP2. The negative results from LEP2 thus exclude the possibility of explicit CP violation in the DSTM at the tree level.

III. EXPLICIT CP VIOLATION AT ONE-LOOP LEVEL

Now, we turn our attention to the possibility of explicit CP violation in the DSTM at the one-loop level. The procedure is quite similar to the tree-level analysis.

On the tree-level mass matrix for the scalar top quarks, \( \mu \) and \( A_t \) may also be complex in general. The complexity of \( \mu \) and \( A_t \) result in the expression for the scalar top quark masses after electroweak symmetry breaking as

\[ m_{t_1, t_2}^2 = \frac{(m_Q^2 + m_T^2)}{2} + m_t^2 + \frac{m_Z^2}{4} \cos 2\beta \pm \sqrt{X_t}, \quad (7) \]

with

\[ X_t = \left[ \frac{m_Q^2 - m_T^2}{2} + \frac{\left( \frac{2}{3} m_{\tilde{u}}^2 - \frac{5m_Z^2}{12} \right) \cos 2\beta}{\tan \beta} \right]^2 + m_t^2 \left( A_t^2 + \frac{\mu^2}{\tan^2 \beta} - \frac{2\mu A_t \cos \varphi}{\tan \beta} \right)^2, \quad (8) \]

where \( m_{\tilde{u}}^2 = g^2 v^2 / 2 \) is the squared mass of \( W \) boson, the top quark mass is given by \( m_t = h_t v_u \), where \( h_t \) is the Yukawa coupling for the top quark, and \( \varphi \) is the overall phase of \( \mu \) and \( A_t \). Note that \( X_t \) represents the mixing between the left-handed and the right-handed scalar top quarks. We do not neglect the \( D \)-term contributions for the scalar top quark masses, as the weak-gauge couplings \( g' \) and \( g \) are included in the above formulae.

The one-loop correction to the Higgs potential is calculated from the effective potential method as [19]

\[ V^1 = \sum_{i=1}^{2} \frac{3M_t^4}{32\pi^2} \log \left[ \frac{M_t^2}{\Lambda^2} - \frac{3}{2} \right] \]

\[ - \frac{3M_t^4}{16\pi^2} \log \left[ \frac{M_t^2}{\Lambda^2} - \frac{3}{2} \right], \quad (9) \]

where \( \Lambda \) is the renormalization scale in the modified minimal subtraction scheme, \( M_t \) and \( \Lambda \) are the field-dependent masses for the scalar top quarks, and \( M_t \) is the field-dependent top quark mass. The total Higgs potential at the one-loop level is thus given by \( V = V^0 + V^1 \).

The mass matrix for the three neutral Higgs bosons at the one-loop level receive contributions from \( V^1 \). Denoting the one-loop contribution as \( M^1 \), the full mass matrix is expressed as

\[ M = M^0 + M^1. \quad (10) \]

The expressions for \( M_{ij} \) \((i, j = 1, 2, 3)\) are identical to the expressions in Ref. [17], where the one-loop contribution is calculated in case of spontaneous CP violation.

As mentioned before, two complex phases, \( \varphi_1 \) and \( \varphi_2 \), are present in \( M^0 \). Now, in \( M^1 \), there is the third one, \( \varphi \). Thus, these three complex phases may trigger explicit CP violation in the DSTM at the one-loop level. However, as in the tree-level case, the tadpole minimum equations at the one-loop level with respect to \( \psi_u \) and \( \psi_d \) reduce the number of independent complex phases. Actually, only one of equations is non-trivial in the explicit CP violation scenario. The equation between complex phases may be expressed as

\[ \sin \varphi_1 = -\frac{\epsilon_2}{\epsilon_1} \cos \beta \sin \beta \sin \varphi_2 - \frac{3m_{\tilde{u}}^2 \mu A_t \sin \varphi}{32\pi^2 v^4 \sin^2 \beta \epsilon_1} f(m_{t_1}^2, m_{t_2}^2), \quad (11) \]

where the second term is the correction at the one-loop level, with a dimensionless function defined as

\[ f(m_{t_2}^2, m_{t_1}^2) = \frac{1}{(m_{\tilde{u}}^2 - m_{\tilde{u}}^2)} \left[ m_{\tilde{u}}^2 \log \frac{m_{\tilde{u}}^2}{\Lambda^2} - m_{\tilde{u}}^2 \log \frac{m_{\tilde{u}}^2}{\Lambda^2} \right] + 1. \quad (12) \]

Using this equation, we may eliminate \( \varphi_1 \), and the remaining \( \varphi_2 \) and \( \varphi \) become responsible for the CP mixing between scalar and pseudoscalar Higgs fields at the one-loop level.

At the one-loop level, the upper bound on the mass of the lightest neutral Higgs boson in the explicit CP violation scenario is modified as

\[ m_{h_1}^2 \leq \frac{1}{2} m_Z^2 \cos^2 (2\beta) + 8\epsilon_1 v^2 \sin (2\beta) \cos (\varphi_1) \]
where $\Delta m_{h_1}$ comes from the radiative corrections due to the loops of top and scalar top quarks. Its expressions is complicated.

We take the mass of top quark as 171 GeV and assume that the mass of top quark is smaller than the masses of the scalar top quarks. We calculate the masses of the three neutral Higgs bosons of the DSTM at the one-loop level. At the one-loop level, the allowed ranges for the relevant parameters are as follows: $2 < \tan \beta < 30$, $|\epsilon_1| < 0.025$, $|\epsilon_2| < 0.025$, $|\varphi_2| < \pi/2$, $|\varphi| < \pi/2$, $0 < m_{A^0} < 1000$ GeV, $100 < |\mu| < 500$ GeV, $|A_t| < 1000$ GeV, and $50 < m_Q = m_T < 500$ GeV. Here, the experimental data on the chargino system are used to set the lower bound on the absolute value of $\mu$. The upper bound on the mass of $h_1$ is about 137 GeV. The masses of the heavier neutral Higgs bosons are calculated to be $16 < m_{h_2} < 1073$ GeV and $112 < m_{h_3} < 1074$ GeV. We show 50,000 points of $(\tan \beta, m_{h_1})$ in Fig. 1, which are obtained by randomly choosing the parameter values in the respectively allowed ranges. One may notice that most of the points in Fig. 1 are above the line $m_{h_1} = 114.5$ GeV, the LEP2 lower bound on the mass of the scalar boson. These points are acceptable, since the negative results for the Higgs search at LEP2 do not exclude these points. However, some of the points are below the LEP2 line. Thus, these points are certainly within the discovery limit of LEP2. We should confirm that the points below the LEP2 line are indeed consistent with the LEP constraints.

For each set of parameter values that yield $m_{h_1} < 114.5$ GeV, we calculate the normalized coupling strengths of the three neutral Higgs bosons to a pair of $Z$ bosons at the one-loop level. These normalized coupling strengths would indeed tell whether the neutral Higgs bosons of the DSTM might have escaped LEP2 or not.

In particular, we examine the normalized coupling coefficients $G_{Zhh_1}$ of the lightest Higgs boson. By randomly varying the parameter values within the same allowed ranges as in Fig. 1, we calculate $G_{Zhh_1}^2$ and $m_{h_1}$. In Fig. 2, we show 50,000 points of $(m_{h_1}, G_{Zhh_1}^2)$ of the lightest Higgs boson at the one-loop level. The general tendency of the distribution in Fig. 2 is that the normalized coupling coefficient becomes larger as the lightest Higgs boson becomes heavier. As the mass of the lightest neutral Higgs boson approaches 114.5 GeV, the LEP2 lower bound on the mass of the SM Higgs boson, the normalized coupling strength grows to 1, that is, it becomes nearly equal to the SM coupling coefficient. This implies that for the parameter values which yield $m_{h_1} \sim 114.5$ GeV and $G_{Zhh_1} \sim 1.0$, the lightest Higgs boson behaves more or less like the SM Higgs boson and the contributions of the heavier Higgs bosons become negligible with respect to decays into a pair of $Z$ bosons.

The result shown in Fig. 2 suggests that the neutral Higgs boson of the DSTM with $m_{h_1} < 114.5$ GeV could not be detected at LEP2. In other words, the explicit CP violation scenario in the DSTM at the one-loop level is consistent with the LEP2 constraints, for the parameter space examined above. Therefore, the possibility of explicit CP violation in the DSTM at the one-loop level is allowed by the present Higgs phenomenology.

![FIG. 1: The distribution of 50,000 points of $(\tan \beta, m_{h_1})$, at the one-loop level. The allowed ranges of the parameter values are: $|\epsilon_1| < 0.025$, $|\epsilon_2| < 0.025$, $|\varphi_2| < \pi/2$, $|\varphi| < \pi/2$, $0 < m_{A^0} < 1000$ GeV, $100 < |\mu| < 500$ GeV, $|A_t| < 1000$ GeV, and $50 < m_Q = m_T < 500$ GeV. Note that the points are evenly distributed with respect to $\tan \beta$, showing no dependence of $m_{h_1}$ on $\tan \beta$. This feature of the DSTM is different from the CP-conserving MSSM, where the maximum of $m_{h_1}$ occurs for large $\tan \beta$.](image-url)
FIG. 2: The distribution of 50,000 points of $(m_{h_1}, G_{ZZh_1}^2)$, the square of normalized coupling strength of the lightest Higgs boson of the DSTM versus its mass, at the one-loop level. The allowed ranges of the parameter values are the same as in Fig. 1.

coupling coefficient to a pair of $Z$ bosons are calculated to be very small, implying that these points are allowed by the LEP2 constraints. Hence, the explicit CP violation scenario in the DSTM at the one-loop level is allowed by the LEP2 data. In conclusion, the DSTM may accommodate explicit CP violation at the one-loop level.

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