New Constraint on Squark Flavor Mixing from $^{199}$Hg Electric Dipole Moment

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Abstract

A new constraint is obtained on the CP-violating flavor mixing between the left-handed top scalar quark ($\tilde{t}_L$) and charm scalar quark ($\tilde{c}_L$), by considering a chargino loop contribution to chromo-electric dipole moment of strange quark, which is limited by the electric dipole moment of the $^{199}$Hg atom. It is found that the flavor mixing should be suppressed to the level of $\mathcal{O}(0.1)$ for the CP phase of order unity, when $\tan\beta$ is relatively large and sparticle masses lie in a few hundred GeV range. Although it is much stronger than the known constraint from the chargino loop contribution to $b \to s\gamma$, the moderate constraint we obtain here is argued to leave room for sizable supersymmetric contribution to the CP asymmetry in $B_d^0 \to \phi K_s$.

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Although low energy supersymmetry (SUSY) is thought to be one of the most promising solutions to the naturalness problem on the electroweak scale inherent in the standard model [1], a random choice of supersymmetry breaking parameters would lead to phenomenological disaster. Contributions from superparticle loops would induce too large flavor changing neutral currents (FCNCs) [2]. Supersymmetric contributions to electric dipole moments (EDMs) would also exceed experimental upper bounds [3]. These two problems are referred to as the SUSY flavor problem and the SUSY CP problem, respectively.

Supersymmetry breaking and its mediation to the standard model sector must therefore be well controlled to avoid the aforementioned disaster. One way to escape from the SUSY flavor problem is to invoke hypothetical degeneracy of masses of squarks and sleptons among different generations. This approach includes minimal supergravity [4], gauge mediation [5], anomaly mediation [6] and gaugino mediation [7,8]. Another way is an alignment mechanism [9–16] of generation mixing of sfermion mass terms with their fermion counterparts. This requires understanding not only sfermion mass generation but also fermion mass generation mechanism. Though appealing, it is rather non-trivial to construct convincing models of flavor.

To see what kind of mediation mechanism really works, it is important to explore possible constraints coming from experimental data. As for the constraints on the mixing of the first two generations, this issue has been studied extensively in the literature (see Ref. [17] and references therein). On the other hand, the constraints involving the third generation are still under study and this is the subject of the present paper.

A remarkable observation has recently been made by Hisano and Shimizu, who have pointed out that supersymmetric contribution to the chromo-electric dipole moment (CEDM) of the strange quark is strongly constrained by the EDM of the $^{199}\text{Hg}$ atom [18]. In particular they have found that a product of left- and right-handed squark mixings suffers from a stringent constraint. This is very interesting because the flavor conserving process (EDM) constrains the flavor mixing of squarks. Moreover the tight constraint on the squark flavor mixings puts an important impact on SUSY contribution to the CP asymmetry in $B^0_d \rightarrow \phi K_s$. In fact, the bound implies that the contribution from $\tilde{b}_R - \tilde{s}_R$ mixing should be extremely small, giving a severe restriction on an interesting scenario where large contribution comes from renormalization group effects of right-handed neutrino Yukawa interaction in grand unified SUSY models [19].

In the present paper, we shall point out that the bound on the EDM of the $^{199}\text{Hg}$ atom gives a new constraint on the up-type left-handed squark mixing when one considers chargino-loop processes. We will compare this constraint with that from $b \rightarrow s \gamma$ and also argue implications to the CP asymmetry in $B^0_d \rightarrow \phi K_s$.

Let us first clarify some notations on the squark masses and mixing used in the literature [20,17]. It is convenient to define

\[
(\delta^{u}_{LL})_{ij} = \frac{(m^2_{\tilde{u}L})_{ij}}{m^2_{\tilde{q}}}, \quad (\delta^{u}_{RR})_{ij} = \frac{(m^2_{\tilde{u}R})_{ij}}{m^2_{\tilde{q}}}, \\
(\delta^{u}_{LR})_{ij} = -\frac{(m^2_{\tilde{u}LR})_{ij}}{m^2_{\tilde{q}}}, \quad (\delta^{u}_{RL})_{ij} = (\delta^{u*}_{LR})_{ji}
\]

(1)

where $(m^2_{\tilde{u}L(R)})_{ij}$ is an $(ij)$ element of the left-handed (right-handed) squark mass squared matrix for up-type squarks in the superCKM basis, in which the Yukawa coupling matrices
are in the diagonal form, and $m_{\tilde{q}}$ is an average squark mass. A similar notation will be used for the down-type squarks.

Next we would like to briefly review the CEDM for quarks and its contribution to the EDM of the $^{199}$Hg atom. We follow Ref. [21]. The effective Hamiltonian for the CEDM for quarks is written

$$H = \sum_{q=u,d,s} d_C^q \frac{i}{2} g_s \bar{q} \sigma^{\mu\nu} T^A \gamma^5 q G^A_{\mu
u},$$

where $g_s$ is the strong coupling constant, $G^A_{\mu\nu}$ represents the gluon field strength with $SU(3)_C$ generator index $A$. The CEDM of the quark $q$ is denoted by $d_C^q$. The EDM of the $^{199}$Hg atom is dominated by the T-odd nuclear force in $\pi^0$ and $\eta$ couplings to nucleons, which is generated by the CEDMs of the constituent quarks. The EDM of the mercury atom was evaluated as

$$d_{Hg} = -e (d^C_d - d^C_u - 0.012 d^C_s) \times 3.2 \times 10^{-2},$$

which is constrained by the existing experimental data, $|d_{Hg}| < 2.1 \times 10^{-28} \text{ e cm}$ at 95% C.L. [22]. Despite the small numerical coefficient in front of $d^C_s$, the strange quark contribution can be important since $d^C_s$ itself is enhanced by a heavier quark mass in the second (and sometimes third) generation. When the contributions from the up and down squarks are absent, the constraint on the EDM of the atom gives the bound to the CEDM of the strange quark as

$$e |d^C_s| < 5.5 \times 10^{-25} \text{ e cm}.$$ 

The chromo-dipole moment may also be constrained by the neutron EDM. However the computation of the latter is more model-dependent\(^1\) and thus we do not consider the constraint coming from the neutron EDM.

Since EDMs are flavor conserving processes, contributions from the (flavor conserving) CP phases of $A$ and $B$ parameters have been extensively discussed in the framework of SUSY models. By imposing the experimental bounds of the EDMs of the electron, neutron and mercury atom on EDM operators generated by flavor diagonal interactions, we obtain $\text{Im } A < 10^{-2} - 10^{-1}$ and $\text{Im } B < 10^{-3} - 10^{-2}$ [23]. Here we do not discuss possible mechanisms to suppress the CP phases of the $A$ and $B$ parameters, and simply assume that they satisfy the bounds given above.

On the other hand, Hisano and Shimizu have found that the bound Eq. (4) gives a very stringent constraint on squark flavor mixing [18]. Specifically they have pointed out that the CP violating part of the product of $(\delta_{LL})_{23}$ and $(\delta_{RR})_{32}$ is strongly constrained. The reason is that in the presence of sizable $\tilde{b}_L - \tilde{s}_L$ and $\tilde{b}_R - \tilde{s}_R$ mixing the dominant contribution

\(^1\)A parton quark model is found to give a severer constraint on the squark flavor mixing from strange quark contribution compared to that from the $^{199}$Hg atom. It is argued, however, that it is likely to be an overestimate [21,23]. More conservative estimation shows the neutron EDM provides a similar limit with the $^{199}$Hg EDM, though it is model-dependent.
to the CEDM of the strange quark arises from the gluino-loop diagram with the \( \tilde{b}_L - \tilde{b}_R \) mixing, which is proportional to \( m_d \mu \tan \beta \), and thus is enhanced by \( m_b/m_s \) over the usual contribution induced by the \( \tilde{s}_L - \tilde{s}_R \) mixing.

Although their constraint is only for the product of \( (\delta_{LL}^d)_{33} \) and \( (\delta_{RR}^d)_{32} \), it practically restricts the phase of \( (\delta_{RR}^d)_{32} \) in most models with high energy SUSY breaking. This is because \( (\delta_{LL}^d)_{33} \) is expected to emerge inevitably at low energy scales due to renormalization group effects even if it is absent at the cutoff scale, say, the Planck scale. At the electroweak scale it is evaluated as \( (\delta_{LL}^d)_{33} \sim 0.01 \) at least unless there is accidental cancellation. Therefore the bound of the \(^{199}\text{Hg EDM}\) constrains the \( 2 - 3 \) mixing in the right-right (RR) sector as \( |\text{Im}(\delta_{RR}^d)_{32}| < O(10^{-3}) \). This has an important implication to \( B^0_d \to \phi K_s \). The Wilson coefficient from the gluino penguin diagrams which contribute to the \( B^0_d \to \phi K_s \) strongly correlates with that for the \(^{199}\text{Hg EDM}\). As a result, the CP asymmetry in \( B^0_d \to \phi K_s \) which originates from the \( \tilde{b}_R - \tilde{s}_R \) mixing should be generically suppressed. This argument leaves \( \tilde{b}_L - \tilde{s}_L \) mixing as a possible source of large CP asymmetry in \( b \to s \) transition. Thus it is important to investigate to what extent large \( \tilde{b}_L - \tilde{s}_L \) mixing is allowed.

We now point out that the LL mixing is also constrained by the \(^{199}\text{Hg EDM}\) bound. We first emphasize that chargino-mediated processes can also provide large contributions to the CEDM of the strange quark \( d^C_s \) because there are diagrams which are enhanced by the top Yukawa coupling constant (See Fig. 1). In the presence of \( 2 - 3 \) mixing in the LL sector, \( d^C_s \) is induced by the double mass insertion diagram in Fig. 1(a) and is evaluated as \(^{2}\)

\[
d^C_s = \frac{1}{32\pi^2}g_y y_s V_{ts} \frac{1}{m^2_{u}} \text{M}_a(x) \text{Im}[\mu(\delta_{RL}^u)_{33}(\delta_{LL}^u)_{32}]
\]

\[
\simeq \frac{1}{8\pi^2} \frac{G_F}{\sqrt{2}} \frac{m^2_t m_s V_{ts}}{m^4_q} \frac{|A_t \mu| \tan \beta}{m^4_q} \text{M}_a(x) |(\delta_{LL}^u)_{32}| \sin \theta_a,
\]

by using the so-called mass insertion method. Here the loop function \( \text{M}_a(x) \) is defined as

\[
\text{M}_a(x) \equiv \frac{1 + 9x - 9x^2 - x^3 + 6x(1 + x) \log x}{(x - 1)^3},
\]

where \( x \equiv |\mu|^2/m^2_q \). One observes that \( \text{M}_a(1) = -0.1, \text{M}_a(0.25) \simeq -0.31 \) and \( \text{M}_a(0) = -1 \). The behavior of the function \( \text{M}_a(x) \) is depicted in Fig. 2. Here the mass insertion parameter \( (\delta_{RL}^u)_{33} \) is given as

\[
(\delta_{RL}^u)_{33} = -\frac{m_t(A_t + \mu^* \cot \beta)}{m^2_q}
\]

and the term proportional to \( \cot \beta \) can be neglected. \( \theta_a \) parameterizes the CP violating phase as \( \theta_a = \text{arg}[A_t \mu (\delta_{LL}^u)_{32}] \). Thus \( d^C_s \) from Fig. 1(a) is estimated as

\(^{2}\)It was shown that the QCD running effect in the CEDM operator Eq.(2) from the weak scale to the hadronic scale is small \([21]\). In fact, the enhancement factor is calculated as \( c \sim 0.9 \), and thus we neglect it in our analysis.
\[
e^C \approx 2.8 \times 10^{-24} \, \text{cm} \times |(\delta_{LL}^u)_{32} \sin \theta_a| \times \left( \frac{\tan \beta}{20} \right) \left( \frac{|\mu|}{250 \, \text{GeV}} \right) \left( \frac{|A_t|}{500 \, \text{GeV}} \right) \left( \frac{m_\tilde{q}}{500 \, \text{GeV}} \right)^{-4} \left( \frac{M_a(x)}{-0.31} \right).
\] (8)

Compared with the experimental upper limit Eq. (4), we obtain
\[
|(\delta_{LL}^u)_{32} \sin \theta_a| < 0.20
\] (9)
for \(\tan \beta = 20\), \(|\mu| = 250 \, \text{GeV}\) and \(|A_t| = m_\tilde{q} = 500 \, \text{GeV}\). Therefore we conclude that the \(\tilde{t}_L - \tilde{c}_L\) mixing angle or the CP violating phase must be suppressed at the level of \(O(0.1)\) when \(\tan \beta\) is large, in the light of the result of the \(^{199}\text{Hg}\) EDM experiment.

It is important to note that \(\tilde{t}_R - \tilde{c}_L\) mixing is induced by a combination of \(\tilde{t}_R - \tilde{t}_L\) and \(\tilde{t}_L - \tilde{c}_L\) mixing through the double mass insertion diagram:
\[
(\delta_{RL}^u)_{32}^{\text{ind}} = -\frac{m_t (A_t + \mu^* \cot \beta)}{m_\tilde{q}^2} \times (\delta_{LL}^u)_{32}.
\] (10)

Based on this observation, it is manifest that \((\delta_{RL}^u)_{32}\) is also constrained considering the diagram in Fig. 1(b). \(d_s^C\) from this contribution is given by
\[
d_s^C \approx \frac{1}{8\pi^2} \frac{G_F}{\sqrt{2}} \frac{|\mu| \tan \beta}{m_\tilde{q}} V_{ts} M_b(x) |(\delta_{RL}^u)_{32}| \sin \theta_b
\] (11)
where
\[
M_b(x) \equiv \frac{1 + 4x - 5x^2 + 2x(2 + x) \log x}{(x - 1)^4}
\] (12)
(See Fig. 2) and \(\theta_b = \arg[\mu(\delta_{RL}^u)_{32}]\). Following the same procedures, the \(\tilde{t}_R - \tilde{c}_L\) mixing parameter is found to be constrained as
\[
|\langle \delta_{LR}^u \rangle_{23} \sin \theta_b | < 5.5 \times 10^{-2}
\] (13)
for the same SUSY parameters as in the \(\tilde{t}_L - \tilde{c}_L\) case.

We stress that the constraint on the mixing parameter \((\delta_{LL}^u)_{32}\) given by Eq. (9) is severer than that obtained from the branching fraction of the process \(b \rightarrow s\gamma\). So far the limit on \(b \rightarrow s\gamma\) was considered to give the strongest bound on \((\delta_{LL}^u)_{32}\) taking chargino-loop diagrams into consideration [24]. However we find that the \(^{199}\text{Hg}\) EDM generically provides severer constraint on \((\delta_{LL}^u)_{32}\) by about one or two orders of magnitude depending on mass spectra of superparticles, provided that the CP phase is of order unity. The same argument is also applied to \((\delta_{LR}^u)_{23}\).

We have dealt with the diagrams shown in Fig. 1 exclusively. Let us consider other possible diagrams producing the CEDM of the strange quark. For example, the constraint on the mixing \((\delta_{LL}^u)_{31}\) is turned out to be weakened by the Cabibbo angle and that on the RR mixing \((\delta_{RR}^u)_{32}\) by about \(m_c/m_t\) compared with that on \((\delta_{LL}^u)_{32}\). Thus we find that the LL mixing \((\delta_{LL}^u)_{32}\) most considerably enhances the chargino-origin dipole moment of the strange quark among off-diagonal elements of the scaler quarks and thus should be bounded most stringently.
Notice that \((\delta^d_{LL})_{ij}\) and \((\delta^d_{LL})_{ij}\) are related to each other because of the \(SU(2)_L\) symmetry. In the superCKM basis, one finds that

\[
(\delta^d_{LL})_{ij} = \sum_{k,l} (V^*_\text{CKM})_{ki}(\delta^u_{LL})_{kl}(V\text{CKM})_{lj},
\]

where \(V\text{CKM}\) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The \((3, 2)\) component can be expanded as

\[
(\delta^d_{LL})_{32} \sim (\delta^u_{LL})_{32} + \lambda (\delta^u_{LL})_{31} + O(\lambda^2)
\]

in terms of the Wolfenstein parameter \(\lambda \sim 0.2\). Thus in the absence of accidental cancellation or hierarchy among the parameters the bound on \((\delta^d_{LL})_{32}\) is translated into that on \((\delta^u_{LL})_{32}\), and vice versa. The severest bound on \((\delta^d_{LL})_{32}\) comes from gluino-mediated \(b \rightarrow s\gamma\) via a double mass insertion [24]. We stress that the constraint on the \(2 - 3\) mixing in the LL sector from the \(^{199}\)Hg EDM is generically as strict as that in this \(b \rightarrow s\gamma\) process, though detailed comparison is sensitive to the SUSY mass spectra.3

Let us now discuss the \(B^0_d \rightarrow \phi K_s\) process, which is known to be one of the most interesting modes. The Belle collaboration [25] has reported the deviation of the CP asymmetry in \(B^0_d \rightarrow \phi K_s\) from the SM prediction, while the latest result from the BaBar collaboration [26] is consistent with the SM prediction. From the theoretical side, CP violation additional to the SM is expected to manifest itself in this process because the tree-level SM contribution is absent. Although it is shown that both \(\tilde{b}_L - \tilde{s}_L\) and \(\tilde{b}_R - \tilde{s}_R\) mixing should be suppressed because of the \(b \rightarrow s\gamma\) and the \(^{199}\)Hg EDM constraints, there still remains some room to cause a sizable effect on the indirect CP-violation parameter \(S_{\phi K_s}\). Notice that the bound on the \(\tilde{b}_L - \tilde{s}_L\) mixing parameter is not as tight as that on \(\tilde{b}_R - \tilde{s}_R\). We emphasize that the prediction of \(S_{\phi K_s}\) can be considerably affected since \(\tilde{b}_L - \tilde{s}_L\) mixing combines with \(\tilde{b}_R - \tilde{b}_L\) mixing to induce significant \(\tilde{b}_R - \tilde{s}_L\) mixing for large \(\tan\beta\) [27–29]. On the contrary, the mass difference between \(B_s\) and \(\bar{B}_s\) would not deviate considerably from its SM prediction under the circumstance and is expected to be measured at Tevatron Run II [28,29]. While the contribution from the induced \(\tilde{b}_R - \tilde{s}_L\) mixing is enhanced in the dipole operators and thus considerably affects \(b \rightarrow s\gamma\) and \(B^0_d \rightarrow \phi K_s\) processes, box diagrams which involve the induced \(\tilde{b}_R - \tilde{s}_L\) mixing are sub-dominant in \(B_s - \bar{B}_s\) mixing.

Here we will discuss loopholes that escape the new bound given above, namely possibilities of cancellation or suppression of the contributions to the \(^{199}\)Hg EDM: (i) As masses of superparticles increase, the contribution to the dipole moment becomes suppressed; (ii) There might be the case where various contributions to the \(^{199}\)Hg EDM cancel out each other. The gluino-loop contribution may cancel out the chargino contribution discussed above. Also, though we have considered the contribution only from the strange quark, it may be possible that the contributions from the up and down quarks compensate it and

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3This argument is applied to the generic case where there is no accidental cancellation or no hierarchy among the squark flavor mixing parameters so that \((\delta^d_{LL})_{32} \sim (\delta^u_{LL})_{32}\). On the other hand, the constraint on the mixing of the up-type squarks Eq. (9) obtained in a previous paragraph is very general.
that the resulting mercury EDM becomes negligible; (iii) The phase of $\mu A_t$ may align with that of $(\delta_{LL}^q)_{32}$ by some mechanism. In fact, the imaginary part of $\mu A_t$ is less constrained by EDM experiments; (iv) There remains theoretical uncertainty in evaluating the EDM of $^{199}\text{Hg}$ atom, which relies on calculations on nuclear and hadron dynamics.

To conclude, we would like to emphasize the importance of constraining the CP-violating $2-3$ mixing in the LL sector. Given the minimal supergravity boundary condition, $(\delta_{LL}^d)_{32}$ emerges from renormalization group running and becomes proportional to $V_{ts}$, and thus its imaginary part is naturally suppressed since there arises no new CP-violating phase except for the CKM matrix. However in the case where the solution of the SUSY flavor problem is attributed to some alignment mechanism based on flavor symmetries generation mixing is expected to be accompanied by large CP-violating phases independent of the CKM matrix. Therefore our new constraint on CP-violating mixing may offer a crucial hint in building models of flavor, which will be discussed elsewhere [30].

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FIG. 1. The dominant Feynman diagrams which contribute to the CEDM of the strange quark via chargino exchange.
FIG. 2. The dependence of the loop functions $M_a$ and $M_b$ on $x = |\mu|^2/m_q^2$. Notice that $-M_a$ is plotted instead of $M_a$. 