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Supersymmetric *R* parity violation and *CP* asymmetry in semileptonic τ decays

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We analyze the *CP* violation in the semileptonic $|\Delta S| = 1$ τ decays in supersymmetric extensions of the standard model with *R* parity violating term. We show that the *CP* asymmetry of τ decay is enhanced significantly and the current experimental limits obtained by CLEO collaborations can be easily accommodated. We argue that observing *CP* violation in semileptonic τ decay would be a clear evidence for *R* parity violating supersymmetry extension of the standard model.

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I. INTRODUCTION

CP violation is one of the main open questions in high energy physics. In the standard model (SM), all *CP* violating observables should be explained by one complex phase $\delta_{\rm CKM}$ in the Cabibbo-Kobayashi-Maskawa (CKM)quark mixing matrix. The effect of this phase was first observed in the kaon system and recently confirmed in *B* decays. The quark-lepton symmetry suggests that the lepton mixing matrix should also violate *CP* invariance. However, the situation in the lepton sector is very different. The only evidence for flavor violation in this sector comes from the neutrino oscillations and there is, so far, no confirmation for *CP* violation in leptonic decays. Hence, measuring *CP* asymmetry in τ decays will open a new window for studying *CP* violation.

In recent papers [1,2], it has been pointed out that $\tau^\pm \to K_{L,S}\pi^\pm\nu$ decays exhibit a *CP* asymmetry of the same size as the one measured in the charge asymmetry of semileptonic K_L decays. This large *CP* asymmetry is induced by the *CP* violation in $K^0 - \bar{K}_0$ mixing. But within the SM, the direct *CP* asymmetry rate of $\tau^\pm \to K^\pm\pi^0\nu$ is of order $O(10^{-12})$ [3]. This nearly vanishing asymmetry implies that the observation of any *CP* asymmetry in this τ decay channel would be a clear signal for the presence of *CP* violation beyond the SM.

Supersymmetry (SUSY) is one of the most interesting candidates for physics beyond the SM. Supersymmetry provides a new source of *CP* violation through complex couplings in the soft SUSY breaking terms. The *CP* asymmetry in the decay mode $\tau^\pm \to K^\pm\pi^0\nu$, in minimal supersymmetric extension of the SM with *R* parity conservation, has been computed in Ref. [4]. It was shown that the SUSY contributions can enhance the *CP* asymmetry rate in τ decay by many orders of magnitude. However, the typical value is of order $O(10^{-7})$ which is still much smaller than the current experimental bound.

The aim of this paper is to show that a significant enhancement for the *CP* asymmetry of $\tau^\pm \to K^\pm\pi^0\nu$ can be obtained in SUSY models with *R* parity violating terms. It turns out that the *R* parity violating terms (in particular, the Lepton number violating ones) induce a tree-level contribution to τ decay. This contribution is proportional to the *R* parity couplings λ and λ', which in general are complex. We find that this new source of *CP* violation enhances the asymmetry of τ decay. We impose new constraints on the couplings λ and λ' from the experimental limits, obtained by CLEO collaborations [5–8].

The paper is organized as follows. In Sec. II, some general features on τ semileptonic decays are recalled. Section III is devoted for analyzing the *CP* asymmetry of $\tau^\pm \to K^\pm\pi^0\nu$ in SUSY models with *R* parity violation. We derive the corresponding effective Hamiltonian and show the terms that violate *R* parity may give significant contribution to the *CP* asymmetry in τ decay. Finally, we give our conclusions in Sec. IV.

II. *CP* ASYMMETRY OF τ SEMILEPTONIC DECAY IN MSSM

In this section we analyze the *CP* asymmetry of τ semileptonic decay modes within the minimal supersymmetric standard model (MSSM); we will focus on the decay mode $\tau^\pm \to K^\pm\pi^0\nu$. The general amplitude for $\tau^-(p) \to K^-(k)\pi^0(k')\nu_\tau(p')$ is given by

$$\mathcal{M} = \frac{G_F V_{us}}{\sqrt{2}}\bigg\{\bar{u}(p')\gamma^\mu(1-\gamma_5)u(p)F_V(t)\bigg[(k-k')_\mu - \frac{\Delta^2}{t}q_\mu\bigg] + \bar{u}(p')(1+\gamma_5)u(p)m_\tau\Lambda F_S(t)\frac{\Delta^2}{t} + F_T\langle K\pi|\bar{s}\sigma_{\mu\nu}u|0\rangle\bar{u}(p')\sigma^{\mu\nu}(1+\gamma_5)u(p)\bigg\},$$

where $q = k + k'$ ($t = q^2$) is the momentum transfer to the hadronic system, and $\Delta^2 \equiv m_K^2 - m_\pi^2$ and $F_{V,S,T}(t)$ are the

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effective form factors describing the hadronic matrix elements. In SM, $F_T = 0$, $\Lambda = 1$

$$\sum_{\text{pols}} |\mathcal{M}|^2 \sim |F_V|^2(2p.Qp'.Q - p.p'Q^2) + |\Lambda|^2|F_S(t)|^2 M^2 p.p' + 2\,\mathrm{Re}\Lambda \cdot \mathrm{Re}(F_S F_V^*) M m_\tau p'.Q - 2\,\mathrm{Im}\Lambda \cdot \mathrm{Im}(F_S F_V^*) M m_\tau p'.Q,$$

where $Q_\mu = (k - k')_\mu - \frac{\Delta^2}{t} q_\mu$.

The last two terms disappear once we integrate on the kinematical variable u unless the form factor has a u dependence. The form factors $F_{V,S}(t)$ can receive weak phase through higher order contributions. Hence, it is possible to generate a CP asymmetry in total decay rates but within SM this CP asymmetry is nearly vanishing [3].

The CP asymmetry is defined as

$$A_{CP} = \frac{\Gamma(\tau^+ \to K^+\pi^0\bar{\nu}_\tau) - \Gamma(\tau^- \to K^-\pi^0\nu_\tau)}{\Gamma(\tau^+ \to K^+\pi^0\bar{\nu}_\tau) + \Gamma(\tau^- \to K^-\pi^0\nu_\tau)}.$$

The effective Hamiltonian H_{eff} derived from SUSY superpotential with R parity symmetry conserved can be expressed as [4]

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{us} \sum_i C_i(\mu) Q_i(\mu), \tag{1}$$

where C_i are the Wilson coefficients and Q_i are the relevant local operators at low energy scale $\mu \simeq m_\tau$. The operators are given by

$$Q_1 = (\bar{\nu}\gamma^\mu L\tau)(\bar{s}\gamma_\mu Lu), \tag{2}$$

$$Q_2 = (\bar{\nu}\gamma_\mu L\tau)(\bar{s}\gamma_\mu Ru), \tag{3}$$

$$Q_3 = (\bar{\nu}R\tau)(\bar{s}Lu), \tag{4}$$

$$Q_4 = (\bar{\nu}R\tau)(\bar{s}Ru), \tag{5}$$

$$Q_5 = (\bar{\nu}\sigma_{\mu\nu}R\tau)(\bar{s}\sigma^{\mu\nu}Ru), \tag{6}$$

where L, R are defined as $L, R = 1 \mp \gamma_5$, and $\sigma^{\mu\nu} = \frac{i}{2} \times [\gamma^\mu, \gamma^\nu]$. The SUSY contributions to the Wilson coefficients C_i can be found in Ref. [4]. For dominant C_3 and/or C_4, one finds that the decay amplitude is given by

$$\mathcal{A}_T(\tau \to K\pi\nu) = \frac{G_F V_{us}}{\sqrt{2}}(1 + C_1)\Big\{ f_V Q^\mu \bar{u}(p')\gamma_\mu Lu(p) + \Big[m_\tau + \Big(\frac{C_3 + C_4}{1 + C_1}\Big)\frac{t}{m_s - m_u}\Big] \times f_S \bar{u}(p')Ru(p)\Big\}.$$

Using the CLEO limit, we can translate this bound into

$$-0.010 \le \mathrm{Im}\Big(\frac{C_3 + C_4}{1 + C_1}\Big) \le 0.004,$$

where we have used $m_s - m_u = 100$ MeV, and the average value $\langle t \rangle \approx (1332.8\ \text{MeV})^2$. However, for $M_1 = 100$ and $M_2 = 200$ GeV and $\mu = M_{\tilde{q}} = 400$ GeV and $\tan\beta = 20$, one gets

$$\mathrm{Im}\Big(\frac{C_3 + C_4}{1 + C_1}\Big) \simeq 1.3 \times 10^{-5}\, \mathrm{Im}(\delta_{21}^d)_{RL}.$$

It is worth noting that the mass insertions $(\delta_{21}^d)_{RL}$ are constrained by the ΔM_K and ϵ_K as follows:

$$|(\delta_{21}^d)_{RL}| \lesssim 4 \times 10^{-3}. \tag{7}$$

Therefore, the resultant CP asymmetry of $\tau \to K\pi\nu$ is smaller than the current experimental limit by a few orders of magnitude.

III. τ DECAY CP ASYMMETRY IN SUSY WITHOUT R PARITY

In this section we study the effect of including terms that violate lepton and baryon number on the tau decay CP asymmetry. The gauge invariance does not insure the conservations of both baryon number and lepton number. Therefore, we can allow the SUSY superpotential to have the R parity violating terms. It is important to mention that R parity violation can be motivated by some controversial experimental observations, like events with missing energy and a hadron jet in the $H1$ experiment at HERA [9]. Recall that the most general superpotential that violates the R parity symmetry can be written as [10]

$$W_{\not{R}p} = \tfrac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \tfrac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2, \tag{8}$$

where a summation over the generation indices $i, j = 1, 2, 3$ and over gauge indices is understood. The λ_{ijk} is an antisymmetric in $\{i, j\}$ because of the contraction of $SU(2)$ indices. Hence, λ_{ijk} are nonvanishing only for $i < j$. The λ''_{ijk} is an antisymmetric in $\{j, k\}$. Therefore $j \neq k$ in $\bar{U}_i\bar{D}_j\bar{D}_k$ and so we can write the superpotential $W_{\not{R}p}$ as

$$W_{\not{R}p} = \lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2. \tag{9}$$

To insure that the proton is stable, we require only the conservation of the baryon number. Thus, we forbid the term $\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$. Expanding the $W_{\not{R}p}$ term into the Yukawa couplings yields

$$\begin{aligned}\mathcal{L} = \lambda_{ijk}[\tilde{\nu}^i_L \bar{e}^k_R e^j_L + \tilde{e}^j_L \bar{e}^k_R \nu^i_L + (\tilde{e}^k_R)^* (\bar{\nu}^i_L)^c e^j_L \\ - (i \leftrightarrow j)] + \lambda'_{ijk}\Big[\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L \\ + (\tilde{d}^k_R)^* (\bar{\nu}^i_L)^c d^j_L - \tilde{e}^i_L \bar{d}^k_R u^j_L - \tilde{u}^j_L \bar{d}^k_R e^i_L \\ - (\tilde{d}^k_R)^* (\bar{e}^i_L)^c u^j_L\Big] + \text{H.c.},\end{aligned} \tag{10}$$

where tilde denotes the scalar fermion superpartners. The leading diagrams for $\tau \to k\pi\nu$ are illustrated in Fig. 1.

The corresponding effective Hamiltonian H_{eff}, derived from SUSY R parity violating terms, can be expressed as

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{us} \sum_i C_i(\mu) Q_i(\mu), \tag{11}$$

where C_i are the Wilson coefficients and Q_i are the relevant local operators at low energy scale $\mu \simeq m_\tau$. These operators are given by

$$Q_1 = (\bar{\nu}\gamma^\mu L\tau)(\bar{s}\gamma_\mu L u), \tag{12}$$

$$Q_2 = (\bar{\nu}R\tau)(\bar{s}Lu), \tag{13}$$

$$Q_3 = (\bar{\nu}L\tau)(\bar{s}Lu). \tag{14}$$

The Wilson coefficients C_i, at the electroweak scale, can be expressed as $C_i = C_i^{\text{SM}} + C_i^{\text{SUSY}}$. For $i = 2, 3$ C_i^{SM} vanish identically. In this respect, the Wilson coefficients C_i are given by

$$C_1 = 1, \tag{15}$$

$$\begin{aligned}C_2 = \frac{\sqrt{2}}{G_F V_{us}}\left(\frac{1}{\tilde{m}^2}\right)(\lambda^*_{123}\lambda'_{212} + \lambda^*_{133}\lambda'_{312} + \lambda^*_{233}\lambda'_{312} \\ + \lambda^*_{323}\lambda'_{212} + \lambda^*_{213}\lambda'_{112} + \lambda^*_{313}\lambda'_{112}),\end{aligned} \tag{16}$$

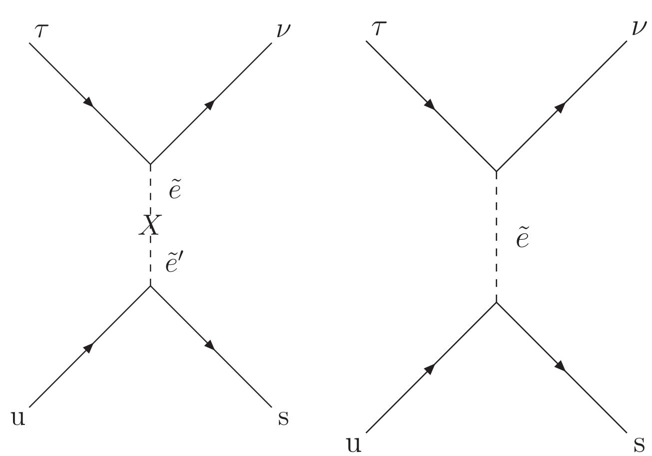

FIG. 1. R parity violation SUSY contributions to $\tau^- \to \bar{u}s\nu_\tau$ transition.

$$C_3 = -\frac{\sqrt{2}}{G_F V_{us}}\left(\frac{1}{\tilde{m}^2}\right)(\lambda_{13k} + \lambda_{23k})(\lambda'_{i12})(\delta^l_{LR})_{ik}. \tag{17}$$

The couplings λ_{ijk} and λ'_{ijk} are generally complex numbers. At a value for $\tilde{m} = 500$ GeV, the upper bounds on these couplings are given as follows [11–13]:

$$\begin{aligned}|\lambda_{131}| = |\lambda_{132}| = 0.3, \qquad |\lambda_{133}| = 0.008, \\ |\lambda_{123}| = 0.25, \qquad |\lambda'_{212}| = 0.3, \qquad |\lambda'_{312}| = 0.6, \\ |\lambda'_{112}| = 0.1, \qquad |\lambda_{i13}\lambda'_{i12}| < 2.425 \times 10^{-2}.\end{aligned} \tag{18}$$

As can be seen from Eq. (17), C_3 is proportional to the mass insertions $(\delta^l_{LR})_{ik}$ which are typically small. Therefore, C_3 can be neglected comparing C_1 and C_2. The decay amplitude for the decay $\tau^-(p) \to K^-(k)\pi^0(k')\nu(p')$ including SM and SUSY contributions becomes

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{us}\{\langle K\pi|\bar{s}\gamma_\mu u|0\rangle \bar{\nu}\gamma_\mu L\tau + C_2\langle K\pi|\bar{s}u|0\rangle \bar{\nu}R\tau\} \tag{19}$$

using

$$\langle K\pi|\bar{s}\gamma_\mu u|0\rangle = f_V(t)Q_\mu + f_S(t)(k + k')_\mu \tag{20}$$

and

$$\langle K\pi|\bar{s}u|0\rangle = \frac{t}{m_s - m_u} f_S(t). \tag{21}$$

The amplitude can be written as

$$\begin{aligned}\mathcal{A}_T(\tau \to K\pi\nu) = \frac{G_F V_{us}}{\sqrt{2}}\Big\{f_V(t)Q^\mu \bar{\nu}(p')\gamma_\mu L\tau(p) \\ + \Big[m_\tau + C_2 \frac{t}{m_s - m_u}\Big] f_S(t)\bar{\nu}(p')R\tau(p)\Big\}.\end{aligned} \tag{22}$$

This expression should be compared with the decay amplitude given in Eq. (2) of Ref. [8]:

$$\begin{aligned}\mathcal{A}(\tau^- \to K\pi\nu_\tau) \sim \bar{u}(p')\gamma_\mu L u(p) f_V Q^\mu \\ + \Lambda\bar{u}(p')Ru(p)f_S M,\end{aligned} \tag{23}$$

where $M = 1$ GeV is a normalization mass scale. Thus, one finds the relation

$$\Lambda M = m_\tau + C_2 \frac{t}{m_s - m_u}. \tag{24}$$

The first term in the last equation is the usual contribution of the SM, which is real, and the second term arises from the SUSY contributions.

Using the bound obtained by the CLEO Collaboration, $-0.172 < \text{Im}(\Lambda) < 0.067$ at 90% C.L. [7], we can translate this bound into

$$-0.010 < \text{Im}C_2 < 0.004, \tag{25}$$

where we have used again as before, $m_s - m_u = 100$ MeV, and the average value $\langle t \rangle \approx (1332.8\ \mathrm{MeV})^2$. After substitution, we can write

$$-0.010 < \frac{\sqrt{2}}{G_F V_{us}} \left(\frac{1}{\tilde{m}^2}\right) \mathrm{Im}\left[\sum_{i,j} (\lambda^*_{ij3} \lambda'_{j12})\right] < 0.004. \tag{26}$$

where $i, j = 1, ..3$. For $G_F = 1.166 \times 10^{-5}$ GeV, $\tilde{m} = 500$ GeV, and $V_{us} = 0.22$, one obtains the following bound:

$$-4.534\,68 \times 10^{-3} < \mathrm{Im}\sum_{i,j} (\lambda^*_{ij3} \lambda'_{j12}) < 1.813\,87 \times 10^{-3}. \tag{27}$$

Thus, with an imaginary part of complex Yukawa couplings λ_{ij3} and/or λ'_{j12} of order 10^{-2}, which are consistent with the limits given in Eq. (18), one can easily satisfy the CLEO constraint on this CP asymmetry. This result is an intrinsic feature for R parity SUSY contribution to the CP asymmetry of $\tau \to K\pi\nu$. It is important to stress that this is the only model, to our knowledge, that enhances CP asymmetry of τ decay significantly and puts this CP asymmetry on the edge of CLEO limits. Therefore, any observation of a CP asymmetry in CLEO would be clear evidence of an R parity violating SUSY extension of the SM.

IV. CONCLUSION

We have studied the supersymmetric contributions to the CP asymmetry of $\tau \to k\pi\nu$ decay. We emphasized that CP asymmetry in this decay is nearly vanishing within the SM. Therefore, any nonvanishing CP asymmetry in this decay channel will be clear evidence for physics beyond the SM. We have shown how physics beyond the standard model as supersymmetric extensions of the SM could induce CP violating asymmetry in the double differential distribution as the CLEO Collaboration did. We find that the CP asymmetry is enhanced by several orders of magnitude more than the SM expectations in case of supersymmetry with conserved R parity. However, the resulting asymmetry is still well below the current experimental limits obtained by CLEO collaborations [4]. Within R parity violation SUSY models, we found that the CP asymmetry of τ decay is enhanced significantly and could put this CP asymmetry within the range of τ decay experiments.

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