One-loop analysis of the four-Fermi contribution to the atomic EDM within RPVMSSM

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Abstract

The contribution in the R-parity violating (RPV) Minimal Supersymmetric Standard Model (MSSM) to the electric dipole moment (EDM) of $^{199}$Hg at the one-loop level is evaluated. At the one-loop level, the $^{199}$Hg EDM receives RPV contribution whose couplings are of a different type from the tree level analysis. This contribution is shown to be constrained by using the limit to the CP-odd electron-nucleon (e-N) interaction given by the recent result of $^{199}$Hg EDM experiment.

1 Introduction

Among the New Physics candidates, the supersymmetric extension of the Standard Model (SM), the MSSM is the most leading one for several reasons. The MSSM has many advantages, namely the cancellation of quadratic divergences in radiative corrections due to the Higgs field, the radiative breaking of the electroweak symmetry, possibility of explaining the dark matter with stable lightest sparticle and so forth.

In MSSM, the lepton and baryon numbers are not necessarily conserved and the conservation of R-parity is assumed to prohibit fast nucleon decays. However, such an assumption is ad hoc, and we must investigate R-parity violation with a close look at phenomenological constraints. We should also note that the coupling constants of RPV interactions are in general complex and therefore provide us with new sources of CP-violation besides the Kobayashi-Maskawa phase in SM. As is known rather well, the baryon/photon ratio in our Universe is hardly explained within SM. Those phases of RPV couplings are of great interest in this respect and should be scrutinized with the help of CP violation observables.

Among observables sensitive to CP violation, electric dipole moment (EDM) may help us reveal mechanism of CP violation. Many EDM measurements including those of neutron, electron and atoms, have been performed until now. In SM, the EDM is predicted to be so small that it turns out to be a very efficient probe of New Physics. In this talk we focus on the atomic EDM which comes from P- and CP-violating e-N interactions.\cite{Herczeg}

Herczeg\cite{Herczeg} pointed out that P- and CP-violating e-N interactions could be produced by sneutrino exchange between electron and quark via RPV-interactions at the tree level. He evaluated such an exchange effect and determined general form of e-N interaction. By comparing it with the atomic EDM ($^{205}$Tl) data then available, Herczeg obtained constraints of the RPV couplings.
Recently, the EDM of $^{199}$Hg was measured by the group of Seattle [3], and the new upper limit was translated into upper bounds on fundamental CP violating parameters. In particular, those of P- and CP-odd e-N interactions have been constrained with unparalleled precision. The purpose of the present work is to confront the P- and CP-odd e-N interactions given in [3] with the theoretical computation at the one-loop level in RPVMSSM. We would like to point out that our one-loop analysis gives constraints on a combination of RPV couplings which are different from Herczeg’s. Our discussion is organized as follows. We first briefly review the R-parity violation and calculate its contribution to the atomic EDM at the one-loop level, then compare it with the new experimental data [3] to obtain bounds on RPV interactions, and finally summarize our results.

2 P- and CP-odd e-N interactions within RPVMSSM

We will consider the P- and CP-violating interactions in RPVMSSM whose interaction Lagrangian is given by

$$\mathcal{L}_R = -\frac{1}{2} \sum_{ijk} \lambda_{ijk} \left( \bar{e}_{Ri} \gamma_{ij}^k \bar{P}_L e_j + \bar{e}_{Li} \bar{e}_k P_L y_i + \bar{\nu}_i \bar{e}_k P_L e_j \right)$$

with $P_L = (1 - \gamma^5)/2$ and $\lambda_{ijk} = -\lambda_{jik}$. Here the indices $i, j, k = 1, 2, 3$ indicate the generations. Many of these RPV interaction terms are constrained phenomenologically [4].

The general form of the P- and CP-odd e-N interaction contributing to the $^{199}$Hg EDM is given by [11]

$$H_{P,T} = \frac{G_F}{\sqrt{2}} \sum_{N=p,n} \left[ C^S_N \, \bar{N} \, \gamma_5 \, e \, + \, C^{PS}_N \, \bar{N} \, i \gamma_5 \, N \, \bar{e} \, + \, C^T_N \, \bar{\nu}_j \, \gamma_j \, N \, \bar{e} \, + \, \bar{\nu}_j \, \gamma_j \, N \, \bar{e} \, + \, \bar{\nu}_j \, \gamma_j \, N \, \bar{e} \, + \right]$$

where $C^S_N$, $C^{PS}_N$ and $C^T_N$ are real parameters. Let us recall that Herczeg [2] evaluated the sneutrino exchange tree-diagram, studied the contributions to $C^S_N$ and $C^{PS}_N$ and deduced phenomenological constraints on

$$\sum_{k=1,2,3} \sum_{j=2,3} \text{Im} \left( \lambda_{1j1} \lambda_{jjk}^\dagger \right).$$

From the recent experimental data of $^{199}$Hg EDM ($dhg = (0.49 \pm 1.29 \pm 0.76) \times 10^{-29} \text{e cm}$ [3]), we obtain the following bounds on P- and CP-odd e-N interactions [11][3]:

$$\left| 0.40 C^S_p + 0.60 C^S_n \right| < 5.2 \times 10^{-8},$$

$$\left| 0.24 C^{PS}_p + 0.76 C^{PS}_n \right| < 5.1 \times 10^{-7},$$

$$\left| 0.24 C^T_p + 0.76 C^T_n \right| < 1.5 \times 10^{-9}.\]
See Ref. [11] for details of derivation of (4) – (6). The SM contributes to these parameters at the level of $10^{-16}$ [5], but the one-loop contribution of some RPV interactions (not constrained at the tree level) can be much larger than these limits.

With the RPV interactions [11], we can construct one-loop corrections to the P- and CP-odd e-N interactions as shown in Fig. 1. The vertex corrections (a) – (g) do not have contributions to $\langle CT \rangle$ and $\langle CS \rangle$.

![Figure 1: Possible one-loop corrections to P- and CP-odd e-N interactions within RPVMSSM.](image)

The EDM for the following reasons: vertex correction can be absorbed in the renormalization of RPV interactions used at the tree level; the RPV couplings give no imaginary part; suppression due to Yukawa couplings. Of course the contributions of one-loop graphs with RPV couplings (3) are already strongly constrained from tree level analysis [2], so we don’t consider them. After detailed analysis, we see that there are only two significant box diagrams, which are shown in Fig. 2. These two contributions are hermitian conjugate of each other and they are summed up into

$$M = -\frac{e^2}{2\sin^2\theta_W} \sum_i \sum_a A_{1i} A'_{1ai} V_{ai} I_{ai} \left[ \bar{e}i\gamma^5 e \cdot \bar{d} - \bar{e}i\gamma^5 \bar{d} e + (P\text{-even terms}) \right] + \text{h.c.}$$

(7)

where $i$ and $a$ are flavor indices. $I_{ai}$ is the loop integral of the box diagram

$$I_{ai} = \frac{1}{4(4\pi)^2} \left[ f(m_{\tilde{e}_i}, m_W, m_u) + f(m_W, m_{\tilde{e}_i}, m_u) + f(m_{u_a}, m_W, m_{\tilde{e}_i}) \right],$$

(8)

where $f(a, b, c) \equiv a^2 \log a^2 / (a^2 - b^2)(a^2 - c^2)$. We shall discuss the dependence of (8) on s-particle mass later. From (4) and (5) we can see that $C_{SP}^{Np}$ is more severely constrained than $C_{PS}^{Np}$ and so we focus on the first term in (7). By using nucleon matrix elements we can derive from (7) the coefficients $C_{SP}^{Np}$ on the nucleon level Hamiltonian (2) as follows:

$$C_{SP}^{Np} = 8m_W^2 \sum_i \sum_a \text{Im}(A_{1i} A'_{1ai}) V_{ai} I_{ai} \langle p | d | p \rangle,$$

(9)

$$C_{SP}^{np} = 8m_W^2 \sum_i \sum_a \text{Im}(A_{1i} A'_{1ai}) V_{ai} I_{ai} \langle p | u | p \rangle,$$

(10)
Figure 2: Box diagrams contributing to P- and CP-odd e-N interactions within RPVMSSM.

where $\langle p|\bar{u}u|p\rangle = 3.5$ and $\langle p|\bar{d}d|p\rangle = 2.8$ were calculated by using isospin symmetry [6] and current quark masses [7]. It should be noted that the RPV couplings $\text{Im}(\lambda^*_{1i1}\lambda'_{ia1})$ in (9) and (10) differ from those in (3). If we could assume that the couplings $\sum_{i,a} \text{Im}(\lambda^*_{1i1}\lambda'_{ia1})$ be much larger than (3), then we could obtain upper limits on RPV interactions $\left|\sum_{i,a} \text{Im}(\lambda^*_{1i1}\lambda'_{ia1})\right|$ by putting (9) and (10) into (4).

The allowed regions of $\left|\text{Im}(\lambda^*_{1i1}\lambda'_{ia1})\right|$ from the constraint (4) are shown in Fig. 3.

Figure 3: The region under the solid line is allowed. In the left (right) figure, the contribution from the charm (top) quark in the loop is taken as the most dominant.

In drawing Fig. 3 we assume implicitly that only one term in the summation in (9) and (10) is much dominant over the others. In the left (right) figure in Fig. 3 the loop diagram in which the charm (top) quark is propagating is taken as the most dominant. As we can see, the upper limits become looser as the selectron mass ($m_{\tilde{e}_Li}$) grows. By setting SUSY particle masses equal to 100 GeV, we obtain the limits to the RPV couplings as shown in Table [1]. We show also the current limits to the RPV couplings from other experimental data [4].

The combinations of the RPV couplings constrained in this discussion differ from those of the tree level analysis by Herczeg [2]. This is simply because we considered W boson exchange diagrams and the CKM flavor change are taken into account. By comparing our limits with the current phenomenological bounds on the RPV interactions from other experiments [4], we see that our one-loop analysis gives tighter constraints by one or two orders of magnitude on the imaginary parts of RPV couplings.
RPV couplings  | Limit from $^{199}$Hg EDM | Limits in Ref. [4]
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$\text{Im}(\lambda^*_1 \lambda'_{221})$ | $7.3 \times 10^{-6}$ | $4.8 \times 10^{-4}$
$\text{Im}(\lambda^*_1 \lambda'_{221})$ | $7.3 \times 10^{-6}$ | $6.0 \times 10^{-4}$
$\text{Im}(\lambda^*_1 \lambda'_{221})$ | $6.0 \times 10^{-4}$ | $8.8 \times 10^{-3}$
$\text{Im}(\lambda^*_1 \lambda'_{221})$ | $6.0 \times 10^{-4}$ | $6.0 \times 10^{-3}$

Table 1: Comparison of the upper bounds on RPV couplings from $^{199}$Hg EDM with other experimental data [4]. Sparticle masses are assumed as $m_{\tilde{t}_L} = 100$ GeV.

3 Summary

To summarize our calculation, we have analyzed the RPV contribution of the P- and CP-odd e-N interactions at the one-loop level and found from the recently updated $^{199}$Hg EDM data [3] new limits on $\text{Im}(\lambda^*_1 \lambda'_{221})$, $\text{Im}(\lambda^*_1 \lambda'_{221})$, $\text{Im}(\lambda^*_1 \lambda'_{221})$, and $\text{Im}(\lambda^*_1 \lambda'_{221})$, as shown in Table 1.

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