Chapter 16
Summary and Future Prospects

Here, we would like to summarize our investigations. We have first reviewed the supersymmetry (SUSY) as a candidate of new physics beyond the standard model (SM). The supersymmetry, although not discovered so far, is one of the leading candidates, because it can provide the stability of the electroweak scale physics by the cancellation of the power divergence. The supersymmetry has been discussed and studied extensively, and the phenomenological works on it are still on-going. We have seen that the R-parity violation, which is one possible scenario of SUSY, is also interesting since it can be linked to the Grand unified theories. In this work, we have studied the R-parity violating (RPV) interactions phenomenologically. The SUSY (and other candidates of new physics) can be probed with a very powerful experimental probe, the electric dipole moments (EDMs), which are the second main subject of this thesis. The EDM is a very sensitive probe of the P and CP violations, with a very small SM background, and it can be measured in a variety of systems, which makes it to be a very good tool to detect the new physics. The EDM played an active role in phenomenology, and many parameters of the SUSY and R-parity violation were constrained by it so far.

In this thesis, we have analyzed the R-parity violation within EDM-constraints, and have reported the following five important results:

- We have revised the two-loop level Barr-Zee type RPV contribution to the fermion EDM. Our result gave a smaller value by about one order of magnitude than previous works. This result alters the relative size between the contribution from P, CP-odd electron–nucleon interactions for the EDM of ^{199}Hg atom.
- We have classified the RPV contribution to the EDM observables. RPV bilinears can be classified into six types. The update of EDM-constraints to the RPV interactions were also given (see Table 13.5). These limits were derived by assuming that only one RPV bilinear dominates.
- We have analyzed the EDM-constraints (^{205}Tl, ^{199}Hg, ^{129}Xe and neutron) on the R-parity violation also for the case where all RPV couplings contributing to the leading order are considered simultaneously. For that we have developed a calculational method based on linear programming. Although being softened (due to

N. Yamanaka, *Analysis of the Electric Dipole Moment in the R-parity Violating Supersymmetric Standard Model*, Springer Theses,
DOI: 10.1007/978-4-431-54544-6_16, © Springer Japan 2014

the interference between RPV bilinears), it was possible to set limits on many RPV bilinears. We have also analyzed the limits on R-parity violation when prospective experimental EDM-constraints of proton, deuteron, ^{3}He nucleus, ^{211}Rn, ^{225}Ra atoms were included in evaluations. These planned EDM experiments have high sensitivity on hadronic RPV bilinears, and within the prospective data, it is possible to constrain them by two orders tighter than the currently available EDM-constraints. We must also note that the interplay of several EDM-constraints can significantly limit the RPV parameter space, and this shows the importance of measuring EDMs on many systems.

- We have also predicted the maximal values for the prospective experiments probing P, CP violation (EDMs of the proton, deuteron, ^{3}He nucleus, ^{211}Rn, ^{225}Ra atoms, and the R-correlation of the neutron beta decay). With the linear programming method, all these observables were predicted with large values. The order of magnitude of their maximal prediction is three or four orders larger than the maximal prediction within the assumption of the dominance of single RPV bilinear. This shows the efficiency of the linear programming method in scanning the RPV parameter space. This result is encouraging for experimentalists because EDMs have more chances to be observed than the suggestions made by analyses within the dominance of single RPV bilinear.
- We have also analyzed the P, CP-odd 4-fermion interactions at the one-loop level, and obtained that some RPV interactions can be constrained by the experimental data of the ^{199}Hg atom. We have obtained a new limit to the CP violating RPV couplings, and have shown the importance of the analysis of the subleading order contribution.

We should add some comments on the advantages of the linear programming method. The first advantage is that the full parameter space can be analyzed taking also the area of the parameter space in which interference and cancellation occur. The second advantage is that the linear programming method can be applied to many other new physics. In particular, if the equation is linear in unknown parameters, the systematic phenomenological study is possible.

With the help of the classification of RPV bilinears, some important consequences were obtained. We have learned that the R-correlation is a useful probe of the RPV bilinear $\mathrm{Im}(\lambda_{i11}\lambda'^*_{i11})$, and if R can be constrained sufficiently by experiments, the type two semi-leptonic RPV bilinears contributing to the P, CP-odd electron–nucleon interactions will be ruled out. We have also learned that the purely hadronic EDMs and muon EDM have restricted sensitivity against RPV bilinears, so that they can be used as a good probe to rule out a specific area of the RPV parameter space. In particular, the muon EDM is the only observable which can probe its RPV contribution, so the muon EDM experiments will play a very important role in the phenomenology of the R-parity violation. Considering all of these results, we have then analyzed the CP violation of the R-parity violation from a very broad point of view.

We have also found many challenging problems in the course of our study. Let us list them:

- A new way to the RPV scenario: In our analysis, we have given the possibility of scenario with large RPV bilinears with some constrained configuration (due to EDM-constraints), which was not possible within the assumption of single coupling dominance. This is a good challenge for theorists to build scenarios of Grand unification with RPV interactions. Theorists however have also to explain naturally the RPV configuration due to the EDM-constraints, which is a challenge.
- Linear programming analysis including the subleading RPV contribution to the EDM: In our analysis all leading RPV contributions are considered simultaneously within EDM-constraints. But we did not add the contribution from the one-loop level P, CP-odd electron–nucleon interaction. As we have concluded that these subleading contributions can also be important, we should add them into the full analysis using the linear programming method. Actually, there are also another subleading contribution in the fermion EDM. This is the Barr-Zee type two-loop level diagram with W-boson exchange, which involves also RPV interactions not relevant at the leading order. To complete this analysis, we should also evaluate this subleading Barr-Zee type diagram, and do the full RPV analysis together with the one-loop P, CP-odd electron–nucleon interaction and the leading contributions.
- Full analysis of the RPV couplings: In our analysis, we have only analyzed the EDM-constraints as linear relations in the linear programming, and the absolute limits on the RPV couplings taken from other experimental data were assumed to hold for single RPV coupling. We have to treat also these absolute limits from other experiments as linear relation inputs in the analysis of linear programming.
- Full analysis of the supersymmetric parameter space: Ideally, this analysis should be extended to the whole supersymmetric parameter space, including the R-parity conserving sector.
- The uncertainty due to QCD: In deriving the EDM of the nucleon, atoms and nuclei, we have encountered uncertainty due to the model calculations of the QCD. The theoretical uncertainty is difficult to estimate, and the result may change even by orders of magnitude. The development of the Lattice QCD is one of the promising framework to do accurate evaluations of the QCD hadron matrix elements. The calculation of the matrix elements needed in the calculation of EDMs is one of the important subjects.
- The uncertainty of the Schiff moment calculation: As can be seen in Table 7.1, the nuclear Schiff moment calculation of the heavy deformed nuclei is rather unstable. This is mainly due to the fact that the ground state wave functions of deformed odd-nuclei are difficult to construct by using the mean-field method. This subject is also a difficult challenge not only for the EDM calculation but also for the nuclear physics.
- Calculations of the EDMs of few body nuclei: We have seen in our thesis that the purely hadronic EDMs have a strong sensitivity against hadronic RPV bilinears. By looking to the sensitivity of the EDMs of deuteron and ^{3}He nucleus to the P, CP-odd pion-nucleon couplings, we see that the sensitivity increases in the number of nuclei. We can therefore expect to have a more sensitive nuclear EDMs for $A = 6$, 7, 8, etc. The recent development of nuclear calculation using *ab initio* approaches

for few body systems is remarkable. The author of this thesis plans to do such calculations as future project.

- Study of the molecular P, CP violation: Recently, the new world record of upper limit to electron EDM was made using YbF molecule. The molecular P, CP violation is a promising study in development since the potential sensitivity of them to new physics is huge, and many researches and developments are on-going. In this thesis, we did not include the constraints from the YbF molecule due to the lack of knowledge about relations between the P, CP violation of the YbF molecule and the underlying P, CP-odd mechanisms. The development of theoretical calculation for molecules is also an important subject.
- Final state interaction contribution of the R-correlation: From our analysis of RPV with linear programming, we have concluded that the improvement of sensitivity of the R-correlation is promising in excluding the degree of freedom of the RPV parameter space allowing large atomic EDMs. The R-correlation receives however contribution from the final state interaction (FSI) which is of order $R_{\rm fsi} \sim 10^{-4}$. To improve the sensitivity of the R-correlation, we must carry out an accurate calculation of the FSI contribution. The R-correlation can also be measured with nuclear beta decay, and for some nuclei such as the ^{8}Li, the FSI contribution is known to be smaller than the neutron. The accurate calculation of the FSI for them are an interesting subject for the R-parity violation.