Chapter 1
Introduction

The construction of the quantum chromodynamics [1–3] and the electroweak theory [4] with three generations of fermions [5] lead to the establishment of the standard model (SM) of particle physics. The SM has been able to describe consistently many data from the accelerator experiments, and all particles except the Higgs boson [6–11] within the model have been discovered so far. We can say that the SM is one of the greatest success of modern physics.

However, despite this great success, particle physicists are not always satisfied with the SM. The SM is actually known to have problems with phenomenology:

- The small mass of neutrinos is difficult to explain in the framework of the SM [12].
- The CP violation due to the CKM mechanism is not sufficient to realize the abundance of the matter in our Universe [13].
- The SM does not have candidates for cold dark matter and hence is not consistent with observations [14–16].
- 73 % of the energy the Universe is filled by the unknown dark energy which cannot be explained in the SM. This fact is suggested by the observations of the type Ia supernovae [17, 18].
- The gravity is not included in the SM.
- Recent experimental data, like the anomalous magnetic moment of the muon or the decay asymmetry of the B hadron show discrepancies from the SM predictions [19–21].

In addition, theoretical and convincing arguments against the SM also exist:

- Hierarchical problem due to the radiative corrections of Higgs scalar. The fundamental Higgs scalar poses a serious problem which requires the SM Higgs parameter to be “ fine-tuned” (at the level of 10^{-34}!!, if the fundamental scale is the Planck scale).
- The choice of gauge group $(SU(3)_c \times SU(2)_L \times U(1)_Y)$ is ad hoc. Many particle physicists believe that this needs the existence of a “Grand unification” of gauge groups to explain.

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_1, © Springer Japan 2014

- The spontaneous breaking of electroweak symmetry is introduced by adjusting the Higgs potential, which is an ad hoc manipulation. The origin of the Higgs scalar and its potential must be explained.
- The flavor structure and masses (Yukawa couplings) of quarks and leptons are given ad hoc. The flavor seems to be arranged in three generations, but their origin is not known.

All these theoretical arguments strongly suggest the existence of a new physics beyond the SM. Especially, the fine-tuning problem due to the radiative correction of Higgs scalar and the ad hoc choice of the Higgs potential give us a hint that the scale of the new physics is relatively close to that of the electroweak symmetry breaking. The problem of the fine-tuning with fundamental scalar particle merits some explanation. The masses of fermions and gauge bosons (with no scalar in the theory) are protected by symmetries. For example, the radiative corrections to the mass m of fermions is $\delta m \propto m \ln(\Lambda/m)$, where Λ is the cutoff of the effective theory. This can be understood by the fact that the radiative correction cannot flip the chirality without the mass insertion, so that $\delta m \propto m$. The radiative corrections to the mass of the gauge boson is ultimately kept zero by the gauge symmetry. The scale dependence of the theory is then only logarithmic, and we have some stability in fixing parameters, such as the masses of particles. When we insert a scalar particle in the theory, however, the situation changes drastically. An example of the radiative correction of the scalar mass at the one-loop level is shown in Fig. 1.1. After performing loop integrations, we obtain that these one-loop corrections both lead to $\delta m \propto \Lambda^2$. What happens in the case of the SM is that the Higgs scalar with mass around $m_H^2 \sim (100\,\text{GeV})^2$ receives corrections of order $\Lambda_{\text{Planck}}^2 \sim (10^{19}\text{GeV})^2$ if the fundamental scale is taken to the Planck scale. This gives a 10^{34} times larger correction! The expected mass of the Higgs boson is $O(100\,\text{GeV})$, so we must tune the parameter of the theory to 1 part in 10^{34}, which seems to be very unnatural. As said above, this fact suggests the existence of a new physics which incorporates the SM as an effective theory near the scale of electroweak symmetry breaking. Theoretically, the resolution of the fine-tuning problem is the most important requirement in constructing models with new physics.

It is generally beleived that the supersymmetric extension of the SM is an important candidate model with new physics. The supersymmetry was first introduced by Wess and Zumino [22]. Thanks to many works, the supersymmetry acquired

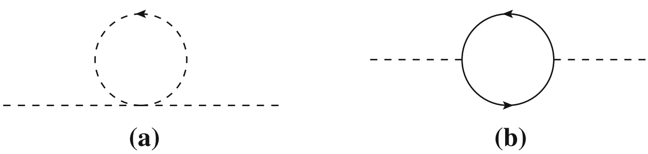

Fig. 1.1 One-loop correction to the scalar mass. *Dashed lines* represent the scalar propagator, and *solid lines* the fermion propagator. **a** Is the correction due to scalar quartic interaction, and (**b**) is the one-loop correction generated by Yukawa interaction

a considerable popularity in particle physics. Compared with the other candidate models with new physics, its phenomenological advantages is particularly interesting [23–26]. Here we can list the following topics:

- The fine-tuning problem due to the radiative corrections of Higgs field can be resolved.
- Soft supersymmetry breaking terms can induce the electroweak symmetry breaking.
- Lightest supersymmetric particles (LSP) can be candidates of dark matters.
- Soft supersymmetry breaking terms can provide new CP violating mechanisms.
- The three running gauge couplings have a better unification at high energy scale.

If the supersymmetry is the true symmetry of the nature, particles discovered so far should have their supersymmetric partners with the same charges and masses. These particles were of course not observed in any past experiments, so we should think that the supersymmetry is a spontaneously broken symmetry. To keep the cancellation of the power divergences in radiative corrections, the supersymmetry must be broken softly. We do not know the definite breaking mechanism of supersymmetry, so the soft breaking terms are introduced by hand. The spontaneous breakdown of supersymmetry is important in phenomenology, since it can provide a new mass scale which is expected to be near above the electroweak scale. The price for introducing the supersymmetry breaking by hand is that we obtain more than 100 soft breaking terms. The soft breaking terms all have mass dimension, and give masses to the particles, which have not been discovered up to 1 TeV [27–31]. The general soft breaking interactions can also have large flavor violation and CP phases, which are also constrained phenomenologically [32]. Other than soft breaking terms, the supersymmetric extension of the SM allows baryon or lepton number violating interactions. These interactions are generated by a set of gauge invariant polynomials of chiral superfields which do not conserve the baryon or lepton numbers, and are called R-parity violating (RPV) interactions. To prevent from such violation, we often assume the conservation of R-parity. This manipulation is however ad hoc. A strong argument to consider RPV interactions comes from the fact that many theoretical physicists believe in the existence of a Grand unified theory of particles and interactions. In Grand unified theories, there are no convincing reasons to distinguish RPV interactions from the R-parity conserving matter fermion-Higgs interactions which give fermion masses, or Higgs self-interactions. Thus it is natural to consider also the violation of R-parity. Many studies of RPV interactions have been done [33–36]. These interactions can generate large baryon number, lepton number, flavor and CP violations, and are therefore strongly constrained by phenomenology.

As discussed above, the models based on the supersymmetric extension of the SM have been studied extensively. To test such models, we can use the available data. But we also need new data which will soon be available from many on-going experiments. The collider experiments at the LHC, through the direct production of new high energy particles, can help to probe the masses of the supersymmetric particles or their lower bounds. There are also many low energy experiments. The Super-K experiments can probe the decay of protons, the mass differences and flavor mixing of neutrinos. The double beta decay experiments will search for the lepton number violations. The muon decay experiments will probe the violation of lepton flavor. Many available experimental results already give significant bounds on parameters of the supersymmetric models, for both R-parity conserving and violating sectors.

In this thesis, we focus on the *electric dipole moments* (EDM), a promising experimental observable which can probe the CP violation originated from the new physics [37–41]. The search for large CP violation is a very important subject in particle physics, since it is known that the CP phase of the CKM matrix cannot provide enough CP violation to realize our matter abundant Universe. In searching for large CP violation, the EDM is an excellent tools for many reasons. First, the EDM is a very "clean" observable. The EDM receives a very small contribution from the SM, due to the higher order effect of the CKM phase. It is also a static observable, so that the final state interaction effects do not disturb the observation. The second important advantage of the EDM is its high accuracy. Due to the strong experimental limits, the EDM has constrained so far many parameters of many candidate models with new physics including the supersymmetry.

The EDM is measurable in a variety of systems, ranging from the elementary particles like the muon to the complex bound states such as molecules. The current experiments already provide very accurate data for each of the systems. The experimental techniques are being improved and many next generation experiments are being prepared, such as the experiments using ultracold neutrons, storage rings, cold molecular beams, ion trap method, etc.

The main objective of this thesis is to investigate the phenomenology of the R-parity violation within the EDM experimental data. There were many previous works in this subject, and many upper limits on the CP violation of the RPV interactions were obtained [42–52]. The RPV interactions contribute to the EDM observables via two leading contributions. The first one is the EDM of quarks and charged leptons, and also the chromo-EDM of quarks. The other contribution is due to the two-body interactions between fermions (lepton-quark, 4-quark and 4-lepton). The trilinear RPV interactions which are the main focus of the study, contribute to the fermion EDM starting from the two-loop level [43, 45]. This is due to the helicity flip of the EDM operator and the structure of the RPV interactions. It was shown by Godbole et al. that the the fermion EDM generated by the RPV contributions at the one-loop level does not exist. The detailed analysis of the two-loop contributions to the fermion EDM due to the R-parity violation was done by Chang et al. They found that the Barr-Zee type two-loop diagrams give the leading contribution, with other suppressed with more than one factor of light quark mass. The P, CP-odd 4-fermion interactions are generated within R-parity violation by sneutrino exchange, and their tree level effects have been studied [46–48].

The two elementary P, CP-odd processes discussed above contribute to experimental EDM observables via intermediate mechanisms, and RPV interactions involved can be constrained by the available experimental data of EDMs of neutron, atoms and molecules. It was shown that the imaginary parts of many bilinears of RPV couplings ($\lambda_{ijj}\lambda^*_{ikk}$, $\lambda_{ijj}\lambda'^*_{ikk}$ and $\lambda'_{ijj}\lambda'^*_{ikk}$, where $i, j, k = 1, 2, 3$) can be constrained via these two processes [43, 45–48]. It is noticed that in those analyses, the dominance of single RPV bilinears is assumed, and the interference between RPV bilinears were neglected.

Recently, we have noticed that the previous calculation of the Barr-Zee type diagram within R-parity violation was not correct [53]. Since the fermion EDM or quark chromo-EDM receive the leading contribution from Barr-Zee type diagram, the entire analysis of EDM within R-parity violation should be revised.

The purpose of this work is to rederive the fermion EDM and the quark chromo-EDM generated from RPV interactions, and analyze the available EDM observables (EDMs of neutron, atoms and molecule) with the corrected formula for Barr-Zee type diagram together with the P, CP-odd 4-fermion interactions. We also predict the EDMs for the planned experiments. As a first step of the extended analysis, we also try to analyze the subleading contribution [54].

In Part I, we briefly review the framework of supersymmetry, the minimal supersymmetric extension of the SM, and the R-parity violation, needed for deriving the P, CP-odd elementary processes contributing to the EDM observables. In order to evaluate the EDM of atoms, nuclei and hadrons, we need to investigate P, CP-odd interactions at the hadronic, nuclear and atomic levels. At each level, we encounter difficult many-body and non-perturbative physics. In this work, we use the best available information on those problems. Part II is a review of the subject on EDM. In Part III, we describe our analysis of the R-parity violation within the EDM-constraints. We first derive the fermion EDM and quark chromo-EDM within the two-loop level Barr-Zee type diagram with detailed explanations of our corrections. Together with the tree level P, CP-odd 4-fermion interaction, we then try to obtain upper bounds on RPV couplings from the atomic, nuclear and hadronic EDM observables using the consequences of the many-body physics presented in Part II. In doing this, we have shown clear classification of RPV bilinears into six types, which clarifies the dependences of the RPV couplings on EDM observables and helps our subsequent analysis. The first step of our phenomenological analysis is to derive upper bounds when single RPV bilinear is considered. This is an update of the previous analyses, including the corrected formula for fermion EDM and quark chromo-EDM. In the next step, we have analyzed RPV contribution to EDMs when all leading RPV bilinears are relevant. In this analysis, the interference between RPV bilinears are also taken into account, within a 10-dimensional parameter space. We also predict the EDM observables for planned experiments. They are also compared between the case of single RPV bilinear dominance and the case where interference can occur. The prospect for each future EDM experiment is discussed from the point of view of the determination of RPV couplings. After that, we present the investigation of one of the subleading contribution to the EDM observables within R-parity violation, the analysis on the P, CP-odd 4-fermion interactions at the one-loop level. This analysis is done by assuming the dominance of one RPV bilinear. This analysis is interesting since the atomic EDMs have a large sensitivity against the P, CP-odd 4-fermion interactions and we can expect that even the subleading RPV contribution can be constrained. It is also the first step of the extended analysis including the subleading RPV contribution to EDM observables. The last chapter is devoted to the summary.

References

1. C.N. Yang, R. Mills, Phys. Rev. **96**, 191 (1954)
2. M. Gell-Mann, Phys. Lett. **8**, 214 (1964)
3. M.Y. Han, Y. Nambu, Phys. Rev. **139**, B1006 (1965)
4. S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967)
5. M. Kobayashi, T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973)
6. F. Englert, R. Brout, Phys. Rev. Lett. **13**, 321 (1964)
7. P.W. Higgs, Phys. Lett. **12**, 132 (1964)
8. P.W. Higgs, Phys. Rev. Lett. **13**, 508 (1964)
9. P.W. Higgs, Phys. Rev. **145**, 1156 (1966)
10. G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett. **13**, 585 (1964)
11. T.W.B. Kibble, Phys. Rev. **155**, 1554 (1967)
12. Y. Fukuda et al., Super-Kamiokande Collaboration. Phys. Rev. Lett. **81**, 1562 (1998)
13. A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (JETP Lett. 5, 24) (1967)
14. F. Zwicky, Astrophys. J. **86**, 217 (1937)
15. M. Davis, G. Efstathiou, C.S. Frenk, S.D.M. White, Astrophys. J. **292**, 371 (1985)
16. D. Clowe et al., Astrophys. J. **648**, L109 (2006)
17. A.G. Riess et al., Supernova Search Team. Astron. J. **116**, 1009 (1998)
18. S. Perlmutter et al., Supernova Cosmology Project. Astrophys. J. **517**, 565 (1999)
19. G.W. Bennett et al., Muon G-2 Collaboration. Phys. Rev. D **73**, 072003 (2006)
20. V.M. Abazov et al., D0 Collaboration, Phys. Rev. Lett. **105**, 081801 (2010)
21. V.M. Abazov et al., D0 Collaboration. Phys. Rev. D **82**, 032001 (2010)
22. J. Wess, B. Zumino, Phys. Lett. **B49**, 52 (1974)
23. H.E. Haber, G.L. Kane, Phys. Rept. **117**, 75 (1985)
24. J.F. Gunion, H.E. Haber, Nucl. Phys. B **272**, 1 (1986)
25. S.P. Martin, arXiv:hep-ph/9709356
26. H. Baer, X. Tata, *Weak Scale Supersymmetry* (Cambridge Univ, Press , 2006)
27. G. Aad et al., ATLAS Collaboration. Phys. Rev. Lett. **106**, 131802 (2011)
28. G. Aad et al., ATLAS Collaboration. Phys. Lett. B **701**, 186 (2011)
29. G. Aad et al., ATLAS Collaboration, arXiv:1110.6189 [hep-ex]
30. V. Khachatryan et al., CMS Collaboration. Phys. Lett. B **698**, 196 (2011)
31. V. Khachatryan et al., CMS Collaboration, arXiv:1111.2733 [hep-ex]
32. F. Gabbiani, E. Gabrielli, A. Masiero, L. Silvestrini, Nucl. Phys. B **477**, 321 (1996)
33. G. Bhattacharyya, arXiv:hep-ph/9709395
34. H.K. Dreiner, arXiv:hep-ph/9707435
35. R. Barbier et al., Phys. Rept. **420**, 1 (2005)
36. M. Chemtob, Prog. Part. Nucl. Phys. **54**, 71 (2005)
37. W. Bernreuther, M. Suzuki, Rev. Mod. Phys. 63, 313 (1991); Erratum-ibid. 64, 633 (1992)
38. I.B. Khriplovich, S.K. Lamoreaux, *CP Vioaltion Without Strangeness* (Springer, Berlin, 1997)
39. J.S.M. Ginges, V.V. Flambaum, Phys. Rept. **397**, 63 (2004)
40. M. Pospelov, A. Ritz, Ann. Phys. **318**, 119 (2005)
41. T. Fukuyama, Int. J. Mod. Phys. A **27**, 1230015 (2012)
42. R. Barbieri, A. Masiero, Nucl. Phys. B **267**, 679 (1986)
43. R.M. Godbole, S. Pakvasa, S.D. Rindani, X. Tata, Phys. Rev. D **61**, 113003 (2000)
44. S.A. Abel, A. Dedes, H.K. Dreiner, JHEP **0005**, 13 (2000)
45. D. Chang, W.-F. Chang, M. Frank, W.-Y. Keung, Phys. Rev. D **62**, 095002 (2000)
46. P. Herczeg, Phys. Rev. D **61**, 095010 (2000)
47. A. Faessler, T. Gutsche, S. Kovalenko, V. E. Lyubovitskij, Phys. Rev. D 73, 114023
48. A. Faessler, T. Gutsche, S. Kovalenko, V.E. Lyubovitskij, Phys. Rev. D **74**, 074013 (2006)
49. K. Choi, E.J. Chun, K. Hwang, Phys. Rev. D **63**, 013002 (2000)
50. Y.Y. Keum, O.C.W. Kong, Phys. Rev. Lett. **86**, 393 (2001)
51. Y.Y. Keum, O.C.W. Kong, Phys. Rev. D **63**, 113012 (2001)
52. C.-C. Chiou, O.C.W. Kong, R.D. Vaidya, Phys. Rev. D **76**, 013003 (2007)
53. N. Yamanaka, T. Sato, T. Kubota, Phys. Rev. D **85**, 117701 (2012)
54. N. Yamanaka, Phys. Rev. D **85**, 115012 (2012)