論文内容の要旨

論文題目
A Model for R-parity Violation and its Phenomenology
（Rパリティーの破れの模型とその現象論）

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The most promising theory beyond the standard model is the supersymmetry, which offers a solution to the hierarchy problem. In addition, in the minimal supersymmetric standard model (MSSM), renormalization group equations for gauge couplings change from those of the standard model, and the unification of gauge groups becomes more plausible. This supports both the ideas of supersymmetry and unification.

In the standard model, all the renormalizable operators conserve the baryon number (B) and the lepton number (L). Thus the proton lifetime is expected to be very long, which is in agreement with the experiments and observations. However, in the MSSM, the gauge symmetry cannot forbid the disastorous operators

$$W \ni \lambda\, L\, \bar{E}\, L + \lambda'\, L\, Q\, \bar{D} + \lambda''\, \bar{D}\, \bar{U}\, \bar{D} \sim \bar{\mathbf{5}}\,\mathbf{10}\,\bar{\mathbf{5}},$$

which lead to too rapid a proton decay. Therefore these operators must be somehow forbidden or strongly suppressed.

The most popular solution to this problem is the R-parity, which forbids these operators altogether. The R-parity is so popular that it is often regarded as a part of MSSM. This is because, the R-parity not only solves this problem, but also has some interesting and attractive features. Among them is the lightest supersymmetric particle (LSP), which can be a good candidate for the dark matter depending on its charge, mass and abundance. The pair-produnction of the LSPs at colliders (such as LHC) is also a characteristic prediction of the R-parity.

However, R-parity is not the only way to avoid the proton decay problem. Various alternative solutions have also been discussed in the literature. Some solutions assume discrete symmetries other than R-parity, so that either the first two operators or the last one are(is) forbidden by the discrete symmetry. In Calabi–Yau compactification of Heterotic $E_8 \times E_8'$ string theory, however, discrete symmetries are found only at special points (or subsets) in moduli space. Reasons are not clear why such vacua have to be chosen.

In the Ph.D. thesis, we presented an alternative solution to the problem without assuming an unbroken symmetry. The essence of the solution is an extra U(1) gauge symmetry with a Fayet–Iliopoulos parameter. The U(1) symmetry is spontaneously broken at high energy, allowing for large Majorana masses of right-handed neutrinos. No unbroken symmetry is left at low energy, but its legacy still remains. There is a selection rule (also known as SUSY-zero mechanism) in how the U(1)-breaking vacuum expectation value (vev) can appear in superpotential of low-energy effective theory, and this rule may be used to make sure that the disastorous operators above are absent.

This solution fits very well with Calabi–Yau compactification of the Heterotic $E_8 \times E_8'$ string theory (and its dual descriptions). In such string compactification, moduli fields are not required to be at special points, and U(1)-symmetry breaking vev is not assumed to be hierarchically small in order to make sure that the disastorous operators above are sufficiently suppressed. Thus, this solution does not share the unsatisfactory aspect of the solutions with discrete symmetries.

Section 2 is a review part of phenomenology, preparing basic knowledge required for the discussions in section 4.

In section 3, the framework for R-parity violation, whose phenomenoloical aspects to be investigated in section 4, is presented. Section 3.1 provides basic knowledge in Calabi–Yau compactification of the Heterotic $E_8 \times E_8'$ string theory. In section 3.2, a class of compactification of the Heterotic string theory is discussed; technically, it is to assume that a vector bundle has an extension structure, and various low-energy degrees of freedom are identified with cohomologies of appropriate sub-bundles. We will see in this framework that holomorphicity controls mixings between *massless* states with different U(1) charges. Thus, the selection rule based on U(1)-charge counting is applied for terms trilinear in massless states, and the absence of R-parity disastorous operators can be guaranteed from the selection rule.

We discuss in sections $3.3 - 3.5$ whether particular kinds of operators are generated or not, and if they are generated, what are the typical scales of these operators. We first look at the R-parity conserving dimension-5 operators that induce proton decay in section 3.3. There we will find that these operators are generated in one model, while they are fobidden in the other. Bilinear R-parity violations are discussed in section

3.4. 1-loop amplitudes generate a bilinear R-parity violating mass term $W \ni \mu_i \, L_i \, H_u$ with μ_i proportional to supersymmetry breaking (SUSY-breaking), and the tree-level contribution can be even smaller. Thus, at the renormalizable level, this framework predicts an R parity violation only in the bilinear terms, which is known not to be terribly bad in phenomenology. In section 3.5, we also find that all the dimension-5 operators that violate R parity are generated; the selection rule does not have a predictive power at non-renormalizable level. With a theoretical framework controlling all aspects of R parity violation, we can discuss how key parameters of short-distance description control the coefficients of various R parity violating operators.

Section 4 is devoted to phenomenology that is expected when both bilinear and dimension-5 R parity violating operators exist. Although small trilinear R-parity violating couplings can be generated in the framework of section 3, it turns out that they are so small that they are rarely relevant to phenomenology. Because of negligibly small trilinear R-parity violation, most of phenomenological constraints discussed so far are easily satisfied, considerably simplifying phenomenological study. Remaining constraints from low-energy neutrino masses and washout of baryon/lepton asymmetry are briefly discussed in sections 4.1 and 4.2, respectively. Constraints on R-parity violating decay of the lightest supersymmetry particle (LSP) are reanalyzed in section 4.3, where we exploit the latest understanding of impact of new physics on the Big–Bang Nucleosynthesis (BBN). Section 4.4 is devoted to limits on R-parity violating couplings from nucleon decay amplitudes. Although trilinear R-parity violating couplings do not induce too rapid a proton decay, squark-exchange diagrams combining bilinear and dimension-5 R-parity violating operators still induce nucleon decay. We will obtain a big picture of allowed region of parameter space of bilinear–dimension-5 R-parity violation, and find that natural expectation of these parameters that follows from the framework in section 3 fits well within the allowed region.

The interesting prediction of our model is the nucleon decay, discussed in section 4.4. Especially, non-vanishing branching fraction of $B - L$ breaking neutron decay $n \to M^+ + \ell^-$ is a robust prediction of our model. $n \to M^+ + \ell^-$ is always predicted except in the decay mode into gravitino, and the decay ratio into gravitino can be at most comparable with other decay mode, even if gravitino mass is very small as $\mathcal{O}(1\text{–}10\,\text{eV})$. This is a notable feature of our model because the observation of $n \to M^+ + \ell^-$ enables us to distinguish it from conventional (SUSY) GUT's, which predict only $B - L$ preserving nucleon decay processes. Moreover, the framework in the section 3 prefer stronger R-parity violation within the allowed parameter region. This means that there is a chance that R-parity violation is confirmed by experiments.