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GUT Scale Threshold Effect on Proton Decay

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The nucleon decay is a significant phenomenon to verify grand unified theories (GUTs). For the precise prediction of the nucleon lifetime induced by the gauge bosons associated with the unified gauge group, it is important to include the renormalization effects on the Wilson coefficients of the dimension-six baryon number violating operators. In this study, we have derived the threshold corrections to these coefficients at the one-loop level in the minimal supersymmetric SU(5) GUT and the extended one with additional SU(5) vector-like pairs. As a result, it is found that the nucleon decay rate is suppressed about 5% in the minimal setup, and then the suppression could be O(10)% in the vector-like matter extensions.

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1. Introduction

The supersymmetric grand unified theories (SUSY GUTs) are attractive extensions of the Standard Model (SM). The gauge groups of the SM are unify into the larger group, such as $SU(5)$, and the SM fields are embedded into the GUT multiplets. SUSY also plays a crucial role in the gauge coupling unification as well as the natural explanation of the gauge hierarchy problem, and we are looking forward to the discovery of the SUSY particles at the LHC experiment. In 2012, it was reported that a scalar particle, which may be consistent with the SM Higgs, was discovered around 126 GeV [1]. The SM is established and we expect the discovery of new physics predicted by the SUSY GUT in near future, although no signal for new physics has been found yet.

It is true that there are several issues which should be carefully studied in the SUSY GUTs. One of the issues is how to achieve the 126 GeV Higgs boson. The minimal supersymmetric standard model (MSSM) is considered as the low-energy effective theory of the SUSY GUTs. It is known, however, that the MSSM predicts the upper bound on the Higgs mass at tree-level, and the observed Higgs mass may require the extension of MSSM or the specific mass spectrum (*e.g.*, the quantum correction to the Higgs mass is enhanced by adding the additional matters [2]).

Another is from the experimental constraints on the baryon-number violating ($\not{B}$) processes, such as nucleon decay, which are induced through the interaction between the GUT and MSSM fields. The current status of the nucleon decay experiments is as follows: $\tau(p \to \pi^0 e^+) > 1.4 \times 10^{34}$ years [3] for the dominant decay mode via a massive gauge boson (X boson), and $\tau(p \to K^+ \overline{\nu}) > 5.9 \times 10^{33}$ years for the dominant mode by the additional color-triplet Higgs exchange [4]. The minimal SUSY $SU(5)$ GUT is excluded by the short partial lifetime of $p \to K^+\overline{\nu}$ if the SUSY scale is close to the electroweak scale [5]. If the SUSY scale is much higher, the constraint from the color-triplet Higgs becomes mild and the dominant decay mode $p \to K^+\overline{\nu}$ may be detected at the future detectors [6]. This dangerous decay mode is also suppressed by extending the models, such as the missing-partner model [7]. Thus, we do not consider the terrible decay mode in this work.

In this talk, we focus on the extra vector-like matter extended models [2]. Since, in these models, the additional fields couple to the SM Higgs field, there is additional contribution to the quantum correction to the Higgs mass. Furthermore, if we introduce the additional fields as complete multiplets of $SU(5)$, the unification of gauge couplings is manifest and these couplings become larger at the GUT scale. Then the nucleon decay through the X-boson exchange is enhanced [8].

This talk is based on our work (ref. [9]). The analytic expression for the threshold corrections to the Wilson coefficients of the $\not{B}$ operators is given in [9]. The GUT mass spectrum dependence of these correction is also shown in the ref. [9], which is not shown in this talk.

2. SUSY $SU(5)$ GUTs

In the SUSY extensions of the SM, matter fields, Higgs fields, and their superpartners are embedded in chiral superfields and their conjugation. Gauge bosons and gauginos are described by vector superfields. In the minimal SUSY $SU(5)$ GUT, the matter fields are given by the $\bar{\mathbf{5}}$ and $\mathbf{10}$ representational superfields which are denoted by Φ and Ψ as follows:

$$\Phi_A(\bar{\mathbf{5}}) = \begin{pmatrix} D^C_\alpha \\ \varepsilon_{rs} L^s \end{pmatrix}, \quad \Psi^{AB}(\mathbf{10}) = \frac{1}{\sqrt{2}} \begin{pmatrix} \varepsilon^{\alpha\beta\gamma} U^C_\gamma & Q^{r\alpha} \\ -Q^{s\beta} & \varepsilon^{sr} E^C \end{pmatrix}, \tag{2.1}$$

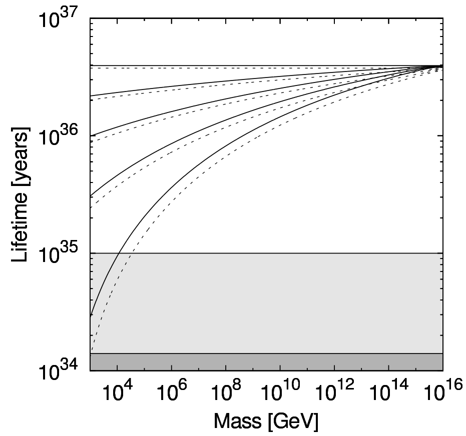

Figure 1: Partial proton lifetime $\tau(p \to \pi^0 + e^+)$ in the vector-like extended SUSY SU(5) models. The solid (dotted) lines describe the lifetime with (without) threshold corrections at GUT scale. The number of vector-like multiplets is set to be $N_{\mathbf{5}} = 0, 1, \cdots, 4$ from top to bottom. The dark gray (gray) region corresponds to the region excluded by Super-Kamiokande (expected the future sensitivity by the Hyper-Kamiokande).

where $A, B, \cdots = 1, 2, \cdots, 5$ are the indices of the $SU(5)$, $\alpha, \beta, \cdots = 1, 2, 3$ and $r, s, \cdots = 1, 2$ are the indices of the $SU(3)_C$ and $SU(2)_L$, respectively. All the chiral superfields include the left-handed fermions in the flavor basis. Q and L denote the weak-doublet chiral superfields for left-handed quarks and left-handed leptons, respectively. U^C, D^C, and E^C denote the chiral superfields for the charge-conjugation of right-handed up-type and down-type quarks, and right-handed charged lepton, respectively. In the Higgs sector, there are **5**, $\bar{\mathbf{5}}$, and **24** representational superfields, especially the **5** and $\bar{\mathbf{5}}$ Higgs multiplets are decomposed as

$$H_{\mathbf{5}}^A(\mathbf{5}) = \begin{pmatrix} H_C^\alpha \\ H_u^r \end{pmatrix}, \quad H_{\bar{\mathbf{5}}A}(\bar{\mathbf{5}}) = \begin{pmatrix} H_{\overline{C}\alpha} \\ \varepsilon_{rs} H_d^s \end{pmatrix}. \tag{2.2}$$

$H_{\mathbf{5}}(\mathbf{5})$ and $H_{\bar{\mathbf{5}}}(\bar{\mathbf{5}})$ include the MSSM Higgs doublets, H_u and H_d. In order to embed the MSSM Higgs multiplets in the $SU(5)$ multiplets, we have to introduce the color-triplet Higgs multiplets H_C and $H_{\overline{C}}$. The adjoint Higgs multiplet (**24**) is introduced to cause the spontaneous symmetry breaking of the $SU(5)$ gauge symmetry according to the non-zero vacuum expectation value (VEV).

3. Results

Let us consider the finite corrections to the $\not{B}$ operators via gauge interactions since the gauge couplings become strong if there exist additional vector-like multiplets. Above the GUT scale, there are three-type finite one-loop corrections to the $\not{B}$ operators; the vacuum polarization of the X boson, the vertex correction to the gauge interactions between the X boson and matter multiplets, and the box corrections. On the other hand, below the GUT scale, the finite corrections arise from the vertex corrections of the dimension-six operators. We calculate the matrix elements for the $\not{B}$ processes with the one-loop finite corrections above and below the GUT scale, and then we determine the threshold corrections to the Wilson coefficients by matching these matrix elements.

In Fig. 1, we show the partial proton lifetime $\tau(p \to \pi^0 + e^+)$ in the vector-like extended SUSY SU(5) models as a function of the mass of vector-like multiplets. For simplicity, all vector-like multiplets are degenerate in mass and the SUSY breaking scale is set to be 1 TeV. The solid and dotted lines correspond in this figure to the case with and without the threshold corrections at GUT scale, respectively.

This figure shows that the threshold corrections at GUT scale correct the matrix elements for nucleon decay maximally 50%, which is correspond to the case that there are four pairs of vector-like multiplets and these masses lie around 1 TeV. On the other hand, in the minimal SUSY $SU(5)$ GUT, the effect of these corrections make the decay rate suppressed about 5%.

4. Conclusion and Discussion

In this talk, we showed the effect of threshold corrections to the Wilson coefficients for the dimension-six $\not{B}$ operators in the minimal SUSY $SU(5)$ GUT and its vector-like matter extensions. Since the gauge couplings at the GUT scale become strong in the vector-like extensions, the higher-order corrections may be significant in order to precisely estimate the lifetime of nucleon. In the minimal SUSY $SU(5)$ GUT, the proton lifetime becomes longer about 5%. On the other hand, in the vector-like extended models, we find the proton decay rate receives $\mathcal{O}(10)\%$ suppression due to the large unified coupling at the GUT scale, maximally about 50% suppression. We note that the precise proton lifetime depends on the nucleon matrix elements. For the calculation of nucleon matrix elements by lattice simulation, there remains about 30% uncertainty [10].

We also note that we neglected the threshold corrections at the SUSY scale and the effect of the additional multiplets at the GUT scale in this work. In order to complete the two-loop level estimation, we need to evaluate the threshold corrections at the SUSY scale. Furthermore, for instance, the additional multiplets are required to solve the doublet-triplet splitting problem in the SUSY $SU(5)$ GUTs. In this work, we estimated all vertex corrections via gauge interactions, so that we need to calculate the vacuum polarization of X boson in order to apply our work in other GUT models. These effects will be shown in the future work.

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