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Nuclear Physics B 910 (2016) 1–22

NUCLEAR PHYSICS B

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Threshold corrections to dimension-six proton decay operators in non-minimal SUSY $SU(5)$ GUTs

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Received 23 March 2016; received in revised form 30 May 2016; accepted 16 June 2016

Available online 21 June 2016

Editor: Hong-Jian He

Abstract

We calculate the high and low scale threshold corrections to the $D = 6$ proton decay mode in supersymmetric $SU(5)$ grand unified theories with higher-dimensional representation Higgs multiplets. In particular, we focus on a missing-partner model in which the grand unified group is spontaneously broken by the **75**-dimensional Higgs multiplet and the doublet–triplet splitting problem is solved. We find that in the missing-partner model the $D = 6$ proton decay rate gets suppressed by about 60%, mainly due to the threshold effect at the GUT scale, while the SUSY-scale threshold corrections are found to be less prominent when sfermions are heavy.

1. Introduction

Grand unified theories (GUTs) are attractive candidates for physics beyond the standard model (SM). The unification of the SM gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ provides a unified description both of gauge interactions and of matter fields. Besides, supersymmetry (SUSY)

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http://dx.doi.org/10.1016/j.nuclphysb.2016.06.017

indicates the precise unification of the SM gauge couplings at the energy scale $\sim 10^{16}$ GeV [1–4] and provides a candidate for dark matter. The discovery of a scalar boson with the mass of 126 GeV [5–7] is consistent with the expectations for the SM Higgs boson. In spite of efforts to find deviations from the SM predictions and/or direct detection of the SUSY particles at the LHC run-2 experiments, no such signal has been found so far, see for instance ATLAS and CMS collaborations reports in Refs. [8–13].

Indirect measurements of rare decays or rare processes are useful to constrain new physics. In particular, SUSY GUTs generically predict nucleon decays by exchanging an additional gauge boson called the X boson ($D = 6$ decay) or a color-triplet Higgs multiplet ($D = 5$ decay). In this paper we will assume that the R-parity violating ($D = 4$ decay) mode is absent or at least negligible.

Regarding the $D = 5$ decay mode it is well-known that the minimal renormalizable SUSY $SU(5)$ GUT in the low-scale SUSY scenario (spartners typically around 1 TeV) has been excluded by predicting a too short lifetime [14,15]. Several ways to relax this severe constraint have been considered. For example, imposing the Peccei–Quinn (PQ) symmetry [16], one can suppress the baryon-number violating terms in the superpotential [17,18]. Similarly, in the high-scale SUSY [19] or split SUSY scenario [20–22], large sfermion masses reduce the Wilson coefficients of the four-Fermi operators responsible for nucleon decay via the color-triplet Higgs multiplet [23,24]. Another possible way to avoid a too fast proton decay rate is to use higher dimensional operators to increase the GUT and triplet scales [25–28] and/or to suppress the color triplet Yukawa couplings without affecting the fermion masses [28,29], or to assume some very specific flavor structure [27]. Last but not least, models originating from higher spacetime dimensions can make use of continuum or discrete symmetries to completely or partially suppress the $D = 5$ mode [30–33]. The bottom line is that the $D = 5$ decay mode is potentially dangerous but very model dependent.

An opposite situation is with the $D = 6$ mode, which is on one side typically slower than the $D = 5$ one, but on the other side more predictive, less model dependent. In this paper we will consider in detail this mode. The results will thus be particularly interesting for models in which for some reason the $D = 5$ mode is negligible and the $D = 6$ one dominates.

The main proton decay mode via the $D = 6$ gauge interaction is into a neutral pion and a positron. For this decay mode various next-to-leading order corrections have been considered: the two-loop renormalization-group equations (RGEs) for the Wilson coefficients in MSSM [34] and SM [35], below the electroweak (EW) scale [36], and the one-loop threshold corrections at the GUT scale in the minimal SUSY $SU(5)$ model [37]. However, such corrections are not available for extended SUSY GUT models, which are motivated by the solution to the doublet–triplet splitting problem. These models typically employ large Higgs representations, so threshold corrections are expected to be particularly important. Since the anomalous dimensions include only gauge couplings at the next-to-leading order, we will focus in the following only on the threshold corrections by gauge interactions.

In this paper we will estimate the threshold effect in SUSY $SU(5)$ GUT models with negligible proton decay via the color-triplet Higgs exchange. As mentioned above, this can be easily obtained for example by imposing a global symmetry such as PQ symmetry. On top of that a light (below the GUT scale) color triplet is typically needed for exact unification [15]. A complete model with both ingredients is the missing-partner model [38,39]: it naturally solves the doublet–triplet splitting problem of the SUSY $SU(5)$ GUT since the $\mathbf{5}$ ($\overline{\mathbf{5}}$) Higgs multiplet only couples to the $\overline{\mathbf{50}}$ ($\mathbf{50}$) multiplet which however does not contain the doublet partner of $\mathbf{5}$ ($\overline{\mathbf{5}}$). Since the adjoint $\mathbf{24}$ cannot couple $\mathbf{5}$ with $\overline{\mathbf{50}}$ (it does couple $\mathbf{5}$ with $\overline{\mathbf{45}}$ [40] though), a higher di-