Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-024-01120-7

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

(Assisted) baryon number violation

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Received 28 August 2023 / Accepted 13 February 2024

Abstract Unlike in 4k dimensions, the action of charge conjugation operator in 4k + 2 dimensions preserves spinor chirality. This property, in a generic orbifolded geometry (of scale $1/R \sim \mathcal{O}$ (1 TeV)) with KK number conservation, leads to baryon number violating operators with KK fermion modes. These exotic operators can be mapped on to the 4D operators responsible for proton decay and hydrogen–antihydrogen oscillation by introducing the KK-1 hypercharge gauge boson interaction. This KK-1 hypercharge gauge boson, being the lightest, is stable and is the ideal dark matter (DM) candidate in the model. Hence, dark matter becomes a crucial ingredient in facilitating the proton decay and $\Delta B = 2 = \Delta L$ processes. Thus, this model answeres the lack of their evidence in terrestrial experiments owing to the low density of dark matter on Earth. Nevertheless, though terrestrial experiments are not yet sensitive to dark matter influenced baryon number violations, their rates can be substantially enhanced in dense DM clusters at the centre of galaxies.

1 Introduction

Baryon–antibaryon asymmetry in the universe has been one of the most intriguing mysteries in nature. With the partial lifetime of proton confirmed to beyond 10^{34} years [1], it is impossible for simple baron number violating New Physics models to exist at $\mathcal{O}$ (1 TeV). On the other hand, next order effects like neutron–antineuron $(n - \bar{n})$ oscillations, $nn \to \bar{\nu}\bar{\nu}$, hydrogen–antihydrogen $(H - \bar{H})$ oscillations, or double proton annihilation $(pp \to e^+e^+)$, which violate baryon number by two units, have been interesting due to the much lower New Physics scale. Such rare processes that violate these accidental symmetries of the standard model (SM) have been very powerful probes to explore physics beyond the standard model. Thus, if detected, it would be of fundamental importance in particle physics and cosmology. In an effective field theory, since both scalar and vector operators lead to $\Delta B = 1$ and $\Delta B = 2$ processes, it is not possible to predict observable $\Delta B = 2$ processes without suppressing $\Delta B = 1$ with discrete symmetries and additional quantum numbers. The solution to these problems might lie in some dynamical process which generate unobservable baryon number violating currents on Earth, but could have had significant contribution to baryogengesis in the evolution of the universe.

In $4k + 2$-dimensions, in particular six dimensions, the anomaly cancellation along with the residual rotational symmetry that survives the orbifolding ensures proton stability [2] naturally. The six-dimensional construction also boasts of a rich phenomenology [3–6], along with providing a viable cold dark matter candidate [7, 8]. Moreover, the analogue of Witten anomaly cancellation, in this geometry, predicts the number of chiral generations [9] that is observed in nature and some of the 6D constructions can lead to small cosmological constant [10] naturally. For the analysis, we construct possible $\Delta B = 1$ and $\Delta B = 2$ operators, assuming B–L conservation for simplicity that are admissible in the T^2/Z_2 orbifold. Here, we discuss the influence of dark matter in proton decay, double proton annihilation producing same sign dilepton states and hydrogen–antihydrogen oscillation in a model-independent effective field theory analysis. We also discuss the proton decay constraint in this geometry and show that the lower bound on the vector operator becomes $\gtrsim 10^6$ TeV. On the other hand, the scalar operator generates proton decay at 1-loop, thus relaxing the constraint on the scale of New Physics to $\gtrsim$ 300 TeV for $\sim \mathcal{O}(1)$ Wilson coefficient. The mixed operators, with scalar and vector bilinear interactions, are not well constrained by any terrestrial measurements. Nevertheless, the signature for these processes are striking. It predicts the same sign, highly collimated, dileptons to be produced with the dark matter–nucelon interaction in the detector. This is a

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highly distinctive track in a calorimeter and water Cherenkov detector. Thus, though the processes are suppressed from Dark Matter density on Earth, they can be enhanced near superdense dark matter clumps.

2 Model

Baryon number violation is usually discussed in a grand unified framework. Due to the power law running of coupling constants in extra-dimensions [11, 12], the unification scale becomes $\sim \mathcal{O}(10^3$ TeV). This could in general be in contradiction with the proton decay constraints. Hence, it is important to understand the possible Lorentz invariant baryon number violating operators the geometry can support. In this section, we discuss the model-independent baryon number violating operators in $4k+2$ dimensions. Though we work with six dimensions to illustrate our arguments, the operators and results can be generalized to any $4k+2$-dimensions with relative ease.

Given that each quark carries 1/3 baryon number, the operator mediating baryon number violation should in general carry $3\Delta B$ quarks. Including lepton number violation as well, a total of $3\Delta B \pm \Delta L$ number of fermions are involved in the process. On compactifying the six dimensions on T^2, the Lorentz generators $\Sigma^{\mu\nu}$ and Σ^{45} remain unbroken. Apart from the four-dimensional Lorentz symmetry, the geometry also exhibits a new rotational symmetry generated by Σ^{45}. Now, orbifolding on a square T^2/Z_2, the rotation symmetry gets broken to a Z_4 symmetry in the $x_4 - x_5$ plane [2]. This property of the space–time, then, requires all the BNV and LNV operators in the geometry to obey the selection rule,

$$\frac{3}{2}\Delta B \pm \frac{1}{2}\Delta L = 0 \text{ mod } 4 \ . \tag{1}$$

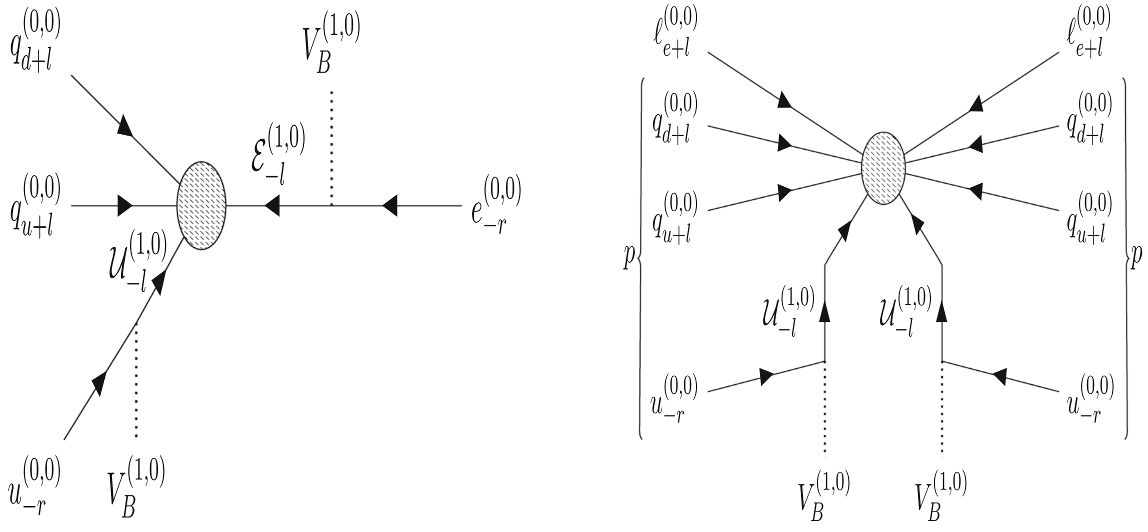
The above relation makes sure that the proton remains stable on a square T^2/Z_2 with $B-L$ conservation. Nevertheless, on a rectangular T^2/Z_2 orbifold, the symmetry group becomes Z_2, and the geometric protection against proton decay vanishes. In which case, the UV-complete model must stabilize the proton beyond the experimental limits.

In a generic T^2/Z_2 rectangular geometry with KK number broken to KK parity conservation, there are non-vanishing operators that involve KK modes. In Table 1, we give the possible operators that arise in six dimensions. Note that there are only operators generated from scalar bilinear, though we start with both scalars and vectors in six dimensions. The vector operators that generate $\Delta B = 1 = \Delta L$, in 4D, consists of at least two KK-1 fermions. This contribution is subdominant to the one from the Wilson coeffcient C_1^V. The same arguments hold for $\Delta B = 2 = \Delta L$ as well. Hence, to the leading order, there are only scalar operators in four dimensions. This would mean that, in a UV complete setup, the origin of such operators arise from the mediation of adjoint scalars in six dimensions.

Figure 1 shows the processes in this model.

3 Results

Here, we show that the proton decay data from Super-Kamiokande constrains any proton decay operator stringently to $\gtrsim 10^6$ TeV. This result is theoretically unpleasant, since the charge unification scale in extra-dimension is much lower ($\mathcal{O}(10^3$ TeV)) owing to the power law running of the gauge couplings. However, the operator that induces proton decay, at 1-loop, is constrained to scale ~ 300 TeV, assuming Wilson Coefficient of order unity. Through the coupling of dark matter with the fermion bilinear, this operator also introduces DM-assisted proton decay with striking signature. This process can be identified in the water Cherenkov detector with collimated rings corresponding to a positron, a pion and missing energy. The lower bound on the New Physics can be brought within the reach of 100 TeV collider, if the Wilson coefficient is assumed to be $C_1^S \lesssim 10^{-3}$. The upcoming hyper-Kamiokande experiment, with its better sensitivity to the proton decay process, will constrain the decay time period to $\tau_{p\to e} \gtrsim 1.2 \times 10^{35}$ years. This will place a stricter bound on the scale of New Physics by a factor $\mathcal{O}(10)$. This scalar operator also induces, with the degeneracy in the KK masses lifted by 1-loop corrections, decay of KK-1 quark to SM fermions and dark matter. The summary of our analysis, with the lower bounds on the scale of New Physics, is given in Table 2.



(a) (b)

Fig. 1 **a** The process $DM + p \to DM + e^+ + \pi^0$ generated through the scalar operator. The stable spinless adjoint scalar field, $V_B^{(1,0)}$, is the dark matter candidate. **b** The processes $DM+p+DM+p \to e^+ + e^+$ and $DM+p \to DM+\bar{p}+e^+ + e^+$ generated by the second term, along with its interaction with $V_B^{(1,0)}$

Table 1 The list of dominant four-dimensional Lorentz invariant operators after compactification

4D Lorentz symmetry	$\Delta B = 1 = \Delta L$	$\Delta B = 2 = \Delta L$
Scalar	$\frac{1}{\Lambda_6^4 R^2} C_1^S (q_{+l}^T C \mathcal{U}_{-l}^{(1,0)})(\mathcal{E}_{-l}^{T(1,0)} C q_{+l})$	$\frac{1}{\Lambda_6^{14} R^6} C_2^V (q_{+l}^T C \Gamma^{4,5} q_{+l})^2 (q_{+l}^T C \Gamma_{4,5} \ell_{+l})^2$
	$\frac{1}{\Lambda_6^4 R^2} C_1^V (q_{+l}^T C \Gamma^{4,5} q_{+l})(q_{+l}^T C \Gamma_{4,5} \ell_{+l})$	$\frac{1}{\Lambda_6^{14} R^6} C_2^Q (q_{+l}^T C \mathcal{E}_{-l}^{(1,0)})^2 (q_{+l}^T C \Gamma^{4,5} q_{+l})^2$
		$\frac{1}{\Lambda_6^{14} R^6} C_2^L (q_{+l}^T C \mathcal{U}_{-l}^{(1,0)})^2 (q_{+l}^T C \Gamma^{4,5} \ell_{+l})^2$

$\Gamma^{4,5}$ in above operators represent either Γ^4 or Γ^5 depending on whether x_4 or x_5 has smaller radius of compactification. The smaller radius of compactification is represented by R

Table 2 Bounds from terrestrial experiments on the New Physics scale Λ_6 from baryon number and lepton number violating observables

Process	Λ_6	Wilson coefficient
Proton decay	$\gtrsim 10^6$ TeV	C_1^V
(1-loop assisted) Proton decay	$\gtrsim 300$ TeV	C_1^S
$p + p \to e^+ + e^+$	$\gtrsim 2.1$ TeV	C_2^V
$DM + p \to DM + \bar{p} + e^+ + e^+$	No constraint	C_2^L
$(DM + e) + p \to (DM + e^+) + \bar{p}$	No constraint	C_2^Q

We have assumed compactification scale to be $R^{-1} = 2$ TeV and Wilson coefficients $\sim \mathcal{O}(1)$

Acknowledgements M.T.A. acknowledges financial support of the ,Department of Science and Technology, Govt. of India, through INSPIRE Faculty grant [DST/INSPIRE/04/2019/002507].

Funding Department of Science and Technology, Govt. of India INSPIRE grant DST/INSPIRE/04/2019/002507.

Data availability statement No data associated with the manuscript.

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