UC San Diego
UC San Diego Previously Published Works

Title

SU(5) Unification without Proton Decay

Permalink

Journal

ISSN

Authors

Fornal, Bartosz
Grinstein, Benjamín

Publication Date

DOI

Peer reviewed

SU(5) Unification without Proton Decay

Bartosz Fornal and Benjamín Grinstein

Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA

(Dated: June 28, 2017)

We construct a four-dimensional renormalizable SU(5) grand unified theory in which the proton is stable. The Standard Model leptons reside in the 5 and 10 irreps of SU(5), whereas the quarks live in the 40 and 50 irreps. The SU(5) gauge symmetry is broken by the vacuum expectation values of the scalar 24 and 75 irreps. All non-Standard Model fields have masses at the grand unification scale. Stability of the proton requires three relations between the parameters of the model to hold. However, abandoning the requirement of absolute proton stability, the model fulfills current experimental constraints without fine-tuning.

I. INTRODUCTION

The Standard Model (SM) of elementary particle physics is based on the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ [1–5]. It is an extremely successful theory and describes Nature remarkably well at the fundamental level. However, the quarks and leptons carry quite specific quantum numbers under this gauge group and the gauge anomaly cancellation occurs rather miraculously. This unexplained feature, along with the desire of finding a larger symmetry of Nature at higher energies, led to the construction of grand unified theories (GUTs).

The first attempt of partial unification was based on the group $SU(4) \times SU(2)_L \times SU(2)_R$ [6], while the seminal papers describing full unification of couplings were those proposing SU(5) [7] and SO(10) [8] gauge groups. Unfortunately, GUTs with complete gauge coupling unification constructed in four dimensions are plagued with proton decay and the current experimental limit [9] excludes their simplest realization. Although there exist many models extending proton lifetime to an experimentally acceptable level, a theoretically interesting question remains: is it at all possible to construct a viable four-dimensional renormalizable GUT based on a single gauge group with an absolutely stable proton?

In this letter we propose such a model. The main idea is simple but the realization is somewhat involved. We present our model rather as a proof of concept, anticipating a simpler realization in the future. An alternative proposal achieves proton stability by imposing gauge conditions that eliminate all non-SM fields from the model [10], resulting in a model that, however, appears to be indistinguishable from the SM. The only other models with a single unifying gauge group designed to completely forbid proton decay we are aware of [11, 12] are experimentally excluded due to the presence of new light particles carrying SM charges.

The most dangerous proton decay channels in GUTs are those mediated by vector leptoquarks and arise from gauge kinetic terms in the Lagrangian. In our model those channels are absent, since the quarks and leptons live in different SU(5) representations. In particular, the leptons reside in the 5 and 10 irreps of SU(5), the right-handed (RH) down quarks are formed from a linear combination of two 50 irreps, whereas the left-handed (LH) quark doublets and the RH up quarks come from a linear combination of two 40 irreps. The SU(5) gauge symmetry is spontaneously broken down to the SM by the

vacuum expectation values (vevs) of scalar field multiplets transforming as 24 and 75 irreps. In order to obtain correct SM masses, the SM Higgs is chosen to be part of a scalar 45 irrep multiplet, and there are no proton decay channels mediated by scalar leptoquarks from the Yukawa terms.

The letter is structured as follows. In Sec. II we present the fermion and scalar content of the theory. Section III contains the relevant Lagrangian terms. In Sec. IV we demonstrate that the SM fermions have SM Yukawa-type masses and all other fields in the theory have masses at the GUT scale. We present conclusions and possible future directions in Sec. V.

II. PARTICLE CONTENT

The model is based on the gauge group SU(5). The fermion sector of the theory is composed of the 5, 10, 40 and 50 irreps, where the 40 and 50 come in two vector-like copies, making the theory anomaly-free. The scalar sector consists of Higgs fields in the 24, 45 and 75 irreps.

A. Fermion sector

The fermion multiplets in the theory come in the following LH spinor field representations, listed below along with their $SU(3)_c \times SU(2)_L \times U(1)_Y$ decomposition [13]:

$$5^c = l \oplus D_5^c$$
$$10 = e^c \oplus Q_{10} \oplus U_{10}^c$$
$$40_i = Q_{40_i} \oplus U_{40_i}^c \oplus (1,2)_{-\frac{3}{2}} \oplus (\bar{3},3)_{-\frac{2}{3}} \oplus (8,1)_1 \oplus (\bar{6},2)_{\frac{1}{6}}$$
$$\overline{40}_i = Q_{\overline{40}_i}^c \oplus U_{\overline{40}_i} \oplus (1,2)_{\frac{3}{2}} \oplus (3,3)_{\frac{2}{3}} \oplus (8,1)_{-1} \oplus (6,2)_{-\frac{1}{6}}$$
$$50_i^c = D_{50_i}^c \oplus (1,1)_2 \oplus (3,2)_{\frac{7}{6}} \oplus (6,3)_{\frac{1}{3}} \oplus (\bar{6},1)_{-\frac{4}{3}}$$
$$\qquad \oplus (8,2)_{-\frac{1}{2}}$$
$$\overline{50_i^c} = D_{\overline{50}_i} \oplus (1,1)_{-2} \oplus (\bar{3},2)_{-\frac{7}{6}} \oplus (\bar{6},3)_{-\frac{1}{3}} \oplus (6,1)_{\frac{4}{3}}$$
$$\qquad \oplus (8,2)_{\frac{1}{2}} \tag{1}$$

where $i = 1, 2$. The lowercase fields l, e are the LH lepton doublet and RH electron, respectively. The fields Q, U and D have the same quantum numbers as the SM's LH quark doublet q and RH quark singlets u and d, respectively.

When coupling to the 5^c, SU(5) gauge bosons can act to transmute an l to an anti-D_5^c, and when coupling to the 10 to transmute Q_{10} to an anti-U_{10}^c. This is the standard route for proton decay in GUTs. If, however, the 5^c multiplet is split, in that the D_5^c mass is comparable to the GUT scale, while that of l arises from electroweak symmetry breaking, and the light d quark arises from a linear combination of the anti-$D_{50_i}^c$, then proton decay cannot proceed through this gauge boson exchange. This is an example of the realization of the mechanism we are proposing for proton stability.

B. Higgs sector

The scalar sector consists of the 24, 45 and 75 irreps of SU(5). Their decomposition into SM multiplets is:

$$24_H = (1,1)_0 \oplus (1,3)_0 \oplus (3,2)_{-\frac{5}{6}} \oplus (\bar{3},2)_{\frac{5}{6}} \oplus (8,1)_0$$

$$45_H = H \oplus (3,1)_{-\frac{1}{3}} \oplus (3,3)_{-\frac{1}{3}} \oplus (\bar{3},1)_{\frac{4}{3}} \oplus (\bar{3},2)_{-\frac{7}{6}}$$
$$\oplus (\bar{6},1)_{-\frac{1}{3}} \oplus (8,2)_{\frac{1}{2}}$$

$$75_H = (1,1)_0 \oplus (3,1)_{\frac{5}{3}} \oplus (\bar{3},1)_{-\frac{5}{3}} \oplus (3,2)_{-\frac{5}{6}} \oplus (\bar{3},2)_{\frac{5}{6}}$$
$$\oplus (\bar{6},2)_{-\frac{5}{6}} \oplus (6,2)_{\frac{5}{6}} \oplus (8,1)_0 \oplus (8,3)_0 . \tag{2}$$

Only the Higgses in the 24 and 75 irreps develop vevs at the GUT scale, which break the SU(5) gauge symmetry down to $SU(3)_c \times SU(2)_L \times U(1)_Y$ [14, 15]. The SM Higgs field H is part of the 45 irrep.

III. LAGRANGIAN

The fermion kinetic terms in the Lagrangian are:

$$\mathcal{L}_{\text{kin}} = i \sum_R \text{Tr}\left(\overline{R}\, \slashed{D}\, R\right) , \tag{3}$$

where the sum is over the representations $R = 5^c, 10, 40_i, \overline{40}_i,$ 50_i^c and $\overline{50}_i^c$. In the standard SU(5) GUT those terms give rise to dangerous dimension-six operators mediating proton decay. In our model such terms generating proton decay are absent, since physical states of SM quarks and leptons reside in different representations of SU(5), as shown in Sec. IV.

The most general gauge-invariant renormalizable Yukawa interactions in our model are given by:

$$\mathcal{L}_Y = 5^c\, Y_l\, 10\, 45_H^* + 40_i\, Y_d^{ij}\, 50_j^c\, 45_H^* + 40_i\, Y_u^{ij}\, 40_j\, 45_H$$
$$+ M_{40}^{ij}\, \overline{40}_i\, 40_j + \lambda_1^{ij}\, 24_H \overline{40}_i\, 40_j + \lambda_2^{ij}\, \overline{40}_i\, 24_H 40_j$$
$$+ \lambda_3^{ij}\, 24_H 10\, \overline{40}_i + \lambda_4^{ij}\, \overline{40}_i\, 75_H 40_j + \lambda_5^i\, 75_H 10\, \overline{40}_i$$
$$+ M_{50}^{ij}\, 50_i^c\, \overline{50}_j^c + \lambda_6^{ij}\, 50_i^c\, 24_H \overline{50}_j^c + \lambda_7^{ij}\, 50_i^c\, 75_H \overline{50}_j^c$$
$$+ \lambda_8^i\, 75_H 5^c\, \overline{50}_i^c + \text{h.c.} \tag{4}$$

with an implicit sum over $i,j = 1,2$, the terms with $\lambda_{1,2}^{ij}$ corresponding to the two independent contractions, and the Hermitian conjugate applied to non-Hermitian terms. We discuss the masses generated by those terms for the $SU(3)_c \times SU(2)_L \times U(1)_Y$ fermion representations in Sec. IV.

It is important to appreciate the crucial property of our model that, along with the absence of proton decay through vector gauge bosons, there is no proton decay mediated by any of the Yukawa-type terms, making the proton absolutely stable. To see this, consider, for example, the first term in Eq. (4): an exchange of the $(\bar{3},2)_{-\frac{7}{6}}$ of the 45 necessarily couples the light lepton doublet l to the GUT-heavy anti-up quark-like U_{10}^c.

The Lagrangian of the scalar sector consists of all possible renormalizable gauge-invariant terms involving the 24, 45 and 75 representations:

$$\mathcal{L}_H = -\tfrac{1}{2}\mu_{24}^2 \text{Tr}(24_H^2) + \tfrac{1}{4}a_1 \left[\text{Tr}(24_H^2)\right]^2 + \tfrac{1}{4}a_2 \text{Tr}(24_H^4)$$
$$- \tfrac{1}{2}\mu_{75}^2 \text{Tr}(75_H^2) + \tfrac{1}{4}\sum b_k \text{Tr}(75_H^4)_k + M_{45}^2 \text{Tr}(|45_H|^2)$$
$$+ \tfrac{1}{2}\sum g_k \text{Tr}(24_H^2 75_H^2)_k + \sum h_k \text{Tr}(24_H^2 |45_H|^2)_k$$
$$+ ... \tag{5}$$

where the index $k = 1, 2, 3$ corresponds to the contractions in which the two lowest representations in a given trace combine into a singlet, a two-component tensor and a four-component tensor, respectively, and a prime is added if more than one contraction in each case exists. For simplicity, we exclude cubic terms in the scalar potential by assuming a $\mathcal{Z}_2$ symmetry of the Lagrangian.

IV. PARTICLE MASSES

In this section we show that there exists a region of parameter space for which all SM fields have standard masses at the electroweak scale and below, whereas all new fields develop GUT-scale masses.

A. Fermion representations 5 and 50

We first focus on the particles in the representation of the down quark. After SU(5) breaking, the corresponding Lagrangian mass terms are:

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} D_{\overline{50}_1} & D_{\overline{50}_2} \end{pmatrix} \mathcal{M}_D \begin{pmatrix} D_5^c \\ D_{50_1}^c \\ D_{50_2}^c \end{pmatrix} \tag{6}$$

with the mass matrix elements

$$\mathcal{M}_D^{i,1} = \tfrac{\sqrt{2}}{3}\lambda_8^i v_{75}$$
$$\mathcal{M}_D^{i,j+1} = M_{50}^{ij} + c_{24}^D \lambda_6^{ij} v_{24} + c_{75}^D \lambda_7^{ij} v_{75} , \tag{7}$$

where v_{24}, v_{75} are the vevs of the representations 24, 75, respectively, $c_{24}^D = 1/(3\sqrt{30})$ and $c_{75}^D = 1/(3\sqrt{2})$. In order to switch to the mass eigenstate basis, we perform a bi-unitary transformation

$$\mathcal{M}_D^{\text{diag}} = (R_D)_{2\times 2}\, \mathcal{M}_D\, (L_D)_{3\times 3}^\dagger \tag{8}$$

and, correspondingly, the mass eigenstates are

$$\begin{pmatrix} D_5^{c\prime} \\ D_{50_1}^{c\prime} \\ D_{50_2}^{c\prime} \end{pmatrix}_L = L_D \begin{pmatrix} D_5^c \\ D_{50_1}^c \\ D_{50_2}^c \end{pmatrix}_L , \quad \begin{pmatrix} D_{\overline{50}_1}' \\ D_{\overline{50}_2}' \end{pmatrix}_R = R_D \begin{pmatrix} D_{\overline{50}_1} \\ D_{\overline{50}_2} \end{pmatrix}_R . \tag{9}$$

Field	$c_{24} \times \sqrt{30}$	$c_{75} \times 3\sqrt{2}$
D_{50}^c	1/3	1
$(1,1)_2$	2	3
$(3,2)_{\frac{7}{6}}$	7/6	1
$(\bar{6},1)_{-\frac{4}{3}}$	$-4/3$	1
$(6,3)_{\frac{1}{3}}$	1/3	-1
$(8,2)_{-\frac{1}{2}}$	$-1/2$	0

TABLE I. Contribution to the masses of the fermion components of the 50^c irrep generated by the Lagrangian terms in Eq. (13).

Field	$c_{24_1} \times \sqrt{30}$	$c_{24_2} \times \sqrt{30}$	$c_{75} \times 3\sqrt{2}$
U_{40}^c	13/9	1/3	5/9
Q_{40}	$-7/9$	$-4/3$	1/9
$(1,2)_{-\frac{3}{2}}$	2	-3	1
$(\bar{3},3)_{-\frac{2}{3}}$	1/3	-3	$-1/3$
$(\bar{6},2)_{\frac{1}{6}}$	1/3	2	$-1/3$
$(8,1)_1$	$-4/3$	2	1/3

TABLE II. Mass contribution generated by the terms involving the scalar 24 and 75 for the fermion components of the 40 irrep.

The unitary matrices L_D and R_D are used to diagonalize the matrices $\left[(\mathcal{M}_D)^\dagger \mathcal{M}_D\right]$ and $\left[\mathcal{M}_D(\mathcal{M}_D)^\dagger\right]$, respectively. From the structure of $\mathcal{M}_D$ we immediately infer that the matrix $\left[(\mathcal{M}_D)^\dagger \mathcal{M}_D\right]$ has one of the eigenvalues equal to zero. In order to completely forbid proton decay, the corresponding eigenstate $D_5^{c\prime}$ cannot contain any admixture of D_5^c. This is achieved by requiring the following tuning of parameters:

$$\det\left(M_{50}^{ij} + c_{24}^D \lambda_6^{ij} v_{24} + c_{75}^D \lambda_7^{ij} v_{75}\right) = 0 . \quad (10)$$

In this case $D_5^{c\prime}$ is a linear combination solely of $D_{50_1}^c$ and $D_{50_2}^c$, and can be associated with the SM field d^c:

$$d^c = L_D^{12} D_{50_1}^c + L_D^{13} D_{50_2}^c , \quad (11)$$

where the matrix entries $L_D^{1,j+1}$ are functions of M_{50}^{ij}, v_{24}, v_{75}, λ_6^{ij}, λ_7^{ij} and λ_8^i.

The condition in Eq. (10) ensures that our model has no proton decay that would involve either a component of the SM lepton doublet l or the down quark d. To our knowledge this novel model building feature has not been discussed in the literature.

If one chooses to abandon the requirement of absolute proton stability, the parameters of the model need not be tuned. Proton decay experimental constraints [9] require merely

$$L_D^{11} \lesssim 0.1 \times \sqrt{(L_D^{12})^2 + (L_D^{13})^2} . \quad (12)$$

The factor of ~ 0.1 can be easily understood: The presence of D_5^c in $D_5^{c\prime}$ would trigger proton decay. The standard SU(5) model predicts proton decay at a rate roughly 100 times larger than the current experimental bound. The contribution to this rate scales like the admixture of D_5^c squared, thus the admixture itself has to be roughly less than 10%.

Finally, one also has to show that all the fields within the 50^c irrep other than D_{50}^c are heavy. For this to be the case, it is sufficient to show that the Lagrangian terms:

$$\Delta \mathcal{L}_{\mathrm{mass}} = \lambda_6^{ij} \, 50_i^c \, 24_H \overline{50_j^c} + \lambda_7^{ij} \, 50_i^c \, 75_H \overline{50_j^c} \quad (13)$$

generate different mass contributions:

$$\Delta \mathcal{M}^{ij} = c_{24}^R \lambda_6^{ij} v_{24} + c_{75}^R \lambda_7^{ij} v_{75} \quad (14)$$

for those representations than for D_{50}^c, since then the equivalent of condition (10) would not be fulfilled for those representations and they would acquire GUT-scale masses. The values of c_{24} and c_{75} are presented in Table I. When combined, these fulfill our requirements. Table I shows that the contribution of the term involving the 75 irrep in Eq. (13) gives the same mass for D_{50}^c as for $(3,2)_{\frac{7}{6}}$ and $(\bar{6},1)_{-\frac{4}{3}}$. The contribution of the term involving the 24 irrep in Eq. (13) breaks this degeneracy.

B. Fermion representations 10 and 40

The analysis for the $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ representations with the quantum numbers of the quark doublet Q and anti-up quark U^c is a little different, since they both reside in the 40 of SU(5). Following the reasoning from the previous case, we arrive at the two conditions:

$$\det\left[M_{40}^{ij} + \left(c_{24_1}^{U,Q} \lambda_1^{ij} + c_{24_2}^{U,Q} \lambda_2^{ij}\right) v_{24} + c_{75}^{U,Q} \lambda_4^{ij} v_{75}\right] = 0 . \quad (15)$$

If these relations are fulfilled, the SM fields u^c and q are not part of the 10 irrep, preventing the proton from decaying through channels involving q, u and e. The values of $c^{U,Q}$ are provided in Table II. Note that Eqs. (15) can be viewed as two quadratic equations, one for c_{75}^U and the second one for c_{75}^Q. The solution to Eq. (15) is then:

$$c_{75}^{U,Q} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A \, v_{75}} , \quad (16)$$

where:

$$A = \lambda_4^{11} \lambda_4^{22} - \lambda_4^{12} \lambda_4^{21}, \quad C = M_{40}^{\prime 11} M_{40}^{\prime 22} - M_{40}^{\prime 12} M_{40}^{\prime 21}$$
$$B = \lambda_4^{11} M_{40}^{\prime 22} - \lambda_4^{12} M_{40}^{\prime 21} - \lambda_4^{21} M_{40}^{\prime 12} + \lambda_4^{22} M_{40}^{\prime 11}$$
$$M_{40}^{\prime ij} \equiv M_{40}^{ij} + c_{24_1}^{U,Q} \lambda_1^{ij} v_{24} + c_{24_2}^{U,Q} \lambda_2^{ij} v_{24} . \quad (17)$$

It is straightforward to check that there exists a class of values for the parameters M_{40}^{ij}, $\lambda_{1,2,4}^{ij}$ fulfilling this requirement, thus forbidding proton decay. The SM u^c and q are given by:

$$u^c = L_U^{12} U_{40_1}^c + L_U^{13} U_{40_2}^c$$
$$q = L_Q^{12} Q_{40_1} + L_Q^{13} Q_{40_2} , \quad (18)$$

where $L_{U,Q}^{1,j+1}$ are functions of M_{40}^{ij}, v_{24}, v_{75}, $\lambda_{1,2,4}^{ij}$ and $\lambda_{3,5}^i$.

The values of $c_{24_1}^R$, $c_{24_2}^R$ and c_{75}^R for the other $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ components of the 40 are provided in Table II. All those representations have different sets of c^R's as compared to U^c and Q and consequently Eq. (15) is not satisfied in those cases. Therefore, those representations develop GUT-scale masses.

C. Scalar representations 24, 45 and 75

In our model the gauge group $\mathrm{SU}(5)$ is broken down to the SM by the GUT-scale vevs of the 24 and 75 irreps, while the 45 does not develop a vev. Stability of the scalar potential is equivalent to the condition that all squared masses of the components of the 24 and 75 irreps are positive, except for one combination of $(3, 2)_{-\frac{5}{6}}$ and one of $(\bar{3}, 2)_{\frac{5}{6}}$ [14–16], the would-be Goldstone bosons of the broken $\mathrm{SU}(5)$. We checked that there exists a large region of parameter space for which all components of the 24 and 75 develop GUT-scale positive squared masses, apart from the $(3, 2)_{-\frac{5}{6}}$ and $(\bar{3}, 2)_{\frac{5}{6}}$ for which the mass-squared matrix is given by

$$\mathcal{M}^2_{(3,2)} = -\frac{1}{18}(g_2 + 11\, g_3 + 15\, g_3') \begin{pmatrix} \frac{v_{75}^2}{5} & \frac{v_{24} v_{75}}{2\sqrt{10}} \\ \frac{v_{24} v_{75}}{2\sqrt{10}} & \frac{v_{24}^2}{8} \end{pmatrix}. \quad (19)$$

We have used relations between parameters satisfied at the stationary point of the potential. The constant of proportionality is a combination of coupling constants, defined in Eq. (5), and can take either sign. The matrix (19) has a vanishing determinant so that one of the linear combinations of the fields is massless while the other has a GUT-scale mass.

The representation 45 does not take part in $\mathrm{SU}(5)$ breaking and its $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ components generically have masses at the GUT scale. Since one of those fields is the SM Higgs, a cancellation between some of the parameters of the potential is required. To show that such an arrangement is possible, it is sufficient to consider only the explicit mass term for the 45 along with the terms mixing it with the 24 in Eq. (5). A small SM Higgs mass contribution is obtained for:

$$M_{45}^2 + \left(h_1 - \frac{67}{240}h_2 + \frac{31}{120}h_2' - \frac{13}{60}h_3 - \frac{5}{16}h_3'\right) v_{24}^2 \simeq 0 \,. (20)$$

We verified that there exists a wide range of parameters for which the GUT-scale masses of all other components of the 45 are positive. The fine-tuning in Eq. (20) is equivalent to the standard $\mathrm{SU}(5)$ doublet-triplet splitting problem and perhaps may be solved by introducing additional $\mathrm{SU}(5)$ representations along the lines of [17, 18].

D. Quark and lepton masses

The SM electron Yukawa emerges from the term:

$$5^c\, Y_l\, 10\, 45_H^* \supset \mathcal{L}_{y_l} = Y_l\, l\, H^* e^c \,. \quad (21)$$

The terms contributing to the SM down quark mass are:

$$40_i\, Y_d^{ij}\, 50_j^c\, 45_H^* \supset \mathcal{L}_{y_d} = y_d^{ij}\, Q_{40i} H^* D_{50j}^c \quad (22)$$

and the down quark Yukawa can be inferred from Eqs. (11), (18) and (22) as a function of the parameters y_d^{ij}, $M_{40,50}^{ij}$, v_{24}, v_{75}, $\lambda_{1,2,4,6,7}^{ij}$ and $\lambda_{3,5,8}^i$. Finally, for the SM up quark we have:

$$40_i\, Y_u^{ij}\, 40_j\, 45_H \supset \mathcal{L}_{y_u} = y_u^{ij}\, Q_{40i} H\, U_{40j}^c \quad (23)$$

and the up quark Yukawa is obtained from Eqs. (18) and (23) as a function of y_u^{ij}, M_{40}^{ij}, v_{24}, v_{75}, $\lambda_{1,2,4}^{ij}$ and $\lambda_{3,5}^i$. There is no need to correct the typical $\mathrm{SU}(5)$ relation between the electron and up quark Yukawas, since they are not directly related in our model.

V. CONCLUSIONS

We have constructed a grand unified model in four dimensions based on the gauge group $\mathrm{SU}(5)$ which does not exhibit proton decay. This accomplished by placing the quarks and leptons in different representations of $\mathrm{SU}(5)$. In order for the proton to be absolutely stable, three relations between the model parameters have to hold. Abandoning the requirement of proton stability removes the necessity of this tuning and the model remains consistent with proton decay experiments for a large range of natural parameter values.

The model has several additional desirable features. It might allow for gauge coupling unification if one of the scalar fields from the 45 representation is at the TeV scale [19–21]. It also contains no problematic relation between the electron and up quark Yukawa plaguing the standard $\mathrm{SU}(5)$ models. However, the usual doublet-triplet splitting problem still persists and requires further model building, perhaps along the lines of a non-supersymmetric version of [17].

Let us stress again that our goal was just to show through an explicit construction that, contrary to common belief, four-dimensional grand unified theories with a stable proton do exist. We hope that this may inspire new directions in model-building efforts and revive the interest in grand unification, which perhaps deserves more attention in spite of negative results from proton decay experiments.

Acknowledgments

[1] S. L. Glashow, "*Partial Symmetries of Weak Interactions*," Nucl. Phys. **22**, 579–588 (1961).

[2] S. Weinberg, "*A Model of Leptons*," Phys. Rev. Lett. **19**, 1264–1266 (1967).

[3] A. Salam, "*Weak and Electromagnetic Interactions*," 8th Nobel Symposium Lerum, Sweden, May 19-25, 1968, Conf. Proc. **C680519**, 367–377 (1968).

[4] H. Fritzsch and M. Gell-Mann, "*Current Algebra: Quarks and What Else?*" Proceedings of the XVI International Conference on High Energy Physics, National Accelerator Laboratory, Chicago, p. 135165 (1972).

[5] H. Fritzsch, M. Gell-Mann, and H. Leutwyler, "*Advantages of the Color Octet Gluon Picture*," Phys. Lett. **B47**, 365–368 (1973).

[6] J. C. Pati and A. Salam, "*Lepton Number as the Fourth Color*," Phys. Rev. **D10**, 275–289 (1974), [Erratum: Phys. Rev. D11, 703 (1975)].

[7] H. Georgi and S. L. Glashow, "*Unity of All Elementary Particle Forces*," Phys. Rev. Lett. **32**, 438–441 (1974).

[8] H. Fritzsch and P. Minkowski, "*Unified Interactions of Leptons and Hadrons*," Annals Phys. **93**, 193–266 (1975).

[9] K. Abe *et al.* (Super-Kamiokande), "*Search for Proton Decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ in 0.31 Megaton·years Exposure of the Super-Kamiokande Water Cherenkov Detector*," Phys. Rev. **D95**, 012004 (2017), arXiv:1610.03597 [hep-ex].

[10] G. K. Karananas and M. Shaposhnikov, "*Gauge Coupling Unification without Leptoquarks*," Phys. Lett. **B771**, 332–338 (2017), arXiv:1703.02964 [hep-ph].

[11] G. Segre and H. A. Weldon, "*SU(5) Theories with Both Proton Stability and Cosmological Baryon Number Generation*," Phys. Rev. Lett. **44**, 1737 (1980).

[12] V. A. Kuzmin and M. E. Shaposhnikov, "*Stable Proton, $n\bar{n}$ Oscillations and Baryon Number Nonconservation at Energies of about 100 GeV*," Phys. Lett. **125B**, 449–451 (1983).

[13] R. Slansky, "*Group Theory for Unified Model Building*," Phys. Rept. **79**, 1–128 (1981).

[14] P. Langacker, "*Grand Unified Theories and Proton Decay*," Phys. Rept. **72**, 185 (1981).

[15] T. Hubsch and S. Pallua, "*Symmetry Breaking Mechanism in an Alternative SU(5) Model*," Phys. Lett. **B138**, 279–282 (1984).

[16] C. J. Cummins and R. C. King, "*Absolute Minima of the Higgs Potential for the 75 of SU(5)*," J. Phys. **A19**, 161 (1986).

[17] B. Grinstein, "*A Supersymmetric SU(5) Gauge Theory with No Gauge Hierarchy Problem*," Nucl. Phys. **B206**, 387 (1982).

[18] A. Masiero, D. V. Nanopoulos, K. Tamvakis, and T. Yanagida, "*Naturally Massless Higgs Doublets in Supersymmetric SU(5)*," Phys. Lett. **B115**, 380–384 (1982).

[19] H. Murayama and T. Yanagida, "*A Viable SU(5) GUT with Light Leptoquark Bosons*," Mod. Phys. Lett. **A7**, 147–152 (1992).

[20] D. C. Stone and P. Uttayarat, "*Explaining the $t\bar{t}$ Forward-Backward Asymmetry from a GUT-Inspired Model*," JHEP **01**, 096 (2012), arXiv:1111.2050 [hep-ph].

[21] P. Cox, A. Kusenko, O. Sumensari, and T. T. Yanagida, "*SU(5) Unification with TeV-scale Leptoquarks*," JHEP **03**, 035 (2017), arXiv:1612.03923 [hep-ph].