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Renormalizable adjoint $SU(5)$

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Abstract

We investigate the possibility to find the simplest renormalizable grand unified theory based on the $SU(5)$ gauge symmetry. We find that it is possible to generate all fermion masses with only two Higgs bosons, 5_H and 45_H. In this context the neutrino masses are generated through the type III and type I seesaw mechanisms. The predictions coming from the unification of gauge couplings and the stability of the proton are discussed in detail. In this theory the leptogenesis mechanism can be realized through the out of equilibrium decays of the fermions in the adjoint representation.

1. Introduction

The possibility to unify all fundamental interactions in nature is one of the main motivations for physics beyond the Standard Model (SM). The so-called grand unified theories (GUTs) are considered as one of the most natural extensions of the Standard Model where this dream is partially realized. Two generic predictions of those theories are the unification of gauge interactions at the high scale, $M_{\text{GUT}} \approx 10^{14-16}$ GeV, and the decay of the lightest baryon [1], the proton, which unfortunately still has not been observed in the experiments.

The first grand unified theory was proposed by Georgi and Glashow in Ref. [2]. As is well known this model, based on $SU(5)$ gauge symmetry, has been considered as the simplest grand unified theory. It offers partial matter unification of one Standard Model family in the anti-fundamental $\bar{5}$ and antisymmetric 10 representations. The Higgs sector is composed of 24_H and 5_H. The GUT symmetry is broken down to the Standard Model by the vacuum expectation value (VEV) of the Higgs singlet field in 24_H, while the SM Higgs resides in 5_H. The beauty of the model is undeniable, but the model itself is not realistic. This model is ruled out for three reasons: the unification of the gauge couplings is in disagreement with the values of α_{em}, $\sin^2\theta_W$ and α_s at the electroweak scale, the neutrinos are massless and the unification of the Yukawa couplings of charged leptons and down quarks at the high scale in the renormalizable model is in disagreement with the experiments.

Recently, several efforts has been made in order to define the simplest realistic extension of the Georgi–Glashow model. The simplest realistic grand unified theory with the Standard Model matter content was pointed out in Ref. [3] where the 15_H has been used to generate neutrino masses and achieve unification. For different phenomenological and cosmological aspects of this proposal see Refs. [4–7]. This theory predicts for the first time the existence of light scalar leptoquarks and that the upper bound on the proton lifetime is $\tau_p \lesssim 2 \times 10^{36}$ years. Therefore, this realistic grand unified theory could be tested at future collider experiments, particularly at LHC, through the production of scalar leptoquarks and at next generation of proton decay experiments. Now, if we extend the Georgi–Glashow model adding extra matter, there is a realistic grand unified model where the extra matter is in the 24 representation. This possibility has been proposed recently by Bajc and Senjanović in Ref. [8]. In this scenario using higher-dimensional operators the neutrino masses are generated through the type I [9] and type III [10] seesaw mechanisms. In this case the theory pre-

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dicts a light fermionic $SU(2)_L$ triplet [8] which is responsible for type III seesaw. See Refs. [8] and [11] for more details.

The type III seesaw mechanism has been proposed for the first time in Ref. [10]. In this case adding at least two fermionic $SU(2)_L$ triplets with zero $U(1)_Y$ hypercharge the effective dimension five operator relevant for neutrino masses are generated once the neutral components of the fermionic triplets are integrated out [10]. In the context of grand unification Ma studied for the first time the implementation of this mechanism in SUSY $SU(5)$ [12]. In this case a fermionic chiral matter superfield in the 24 representation has to be introduced [12] and the neutrino masses are generated through type I and type III seesaw mechanisms since in the 24 representation one has the fermionic triplet responsible for type III seesaw and a singlet responsible for type I seesaw. Therefore, if we want to realize the type III seesaw mechanism one must introduce extra matter in the adjoint representation. The implementation of this mechanism in non-SUSY $SU(5)$ has been understood in Ref. [8]. In this case they have introduced extra matter in the 24 representation and use higher-dimensional operators in order to generate at least two massive neutrinos and a consistent relation between the masses of charged leptons and down quarks [8].

The models mentioned above include the whole set of higher-dimensional operators in order to have a consistent relation between the Yukawa couplings at the unification scale. In this work we want to stick to the renormalizability principle and focus our attention on renormalizable extensions of the Georgi–Glashow model. Following the results presented in Refs. [12] and [8] we investigate the possibility to write down the simplest renormalizable grand unified theory based on the $SU(5)$ gauge symmetry. We find that it is possible to generate all fermion masses at the renormalizable level, including the neutrino masses, with the minimal number of Higgs bosons: 5_H and 45_H. The implementation of the leptogenesis mechanism [13] is possible. In this model the leptogenesis mechanism can be realized through the out of equilibrium decays of the fermions in the adjoint representation. Notice that in the model proposed in Ref. [8] only resonant leptogenesis could be possible since the fermionic triplet is very light. As we will show in the next section there is no problem to satisfy the experimental lower bounds on the proton decay lifetime. We propose a new renormalizable grand unified theory based on the $SU(5)$ gauge symmetry with extra matter in the adjoint representation. We refer to this theory as “renormalizable adjoint $SU(5)$”. The model proposed in this Letter can be considered as the renormalizable version of the model given in Ref. [8] and is one of the most appealing candidates for the unification of the Standard Model interactions at the renormalizable level. In the next sections we discuss some of the most relevant phenomenological aspects of this proposal.

2. Renormalizable adjoint $SU(5)$

In order to write down a realistic grand unified theory we have to be sure that all constraints coming from the unification of gauge couplings, fermion masses and proton decay can be satisfied. In this Letter we stick to the simplest unified gauge group, $SU(5)$, and to the renormalizability principle. Now, if we want to have a consistent relation between the masses of charged leptons and down quarks at the renormalizable level we have to introduce the 45_H representation [14]. Therefore, our Higgs sector must be composed of $24_H = (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\bar{3},2)}, \Sigma_{24}) = (8,1,0) \oplus (1,3,0) \oplus (3,2,-5/6) \oplus (\bar{3},2,5/6) \oplus (1,1,0)$, $45_H = (\Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5, \Phi_6, H_2) = (8,2,1/2) \oplus (\bar{6},1,-1/3) \oplus (3,3,-1/3) \oplus (\bar{3},2,-7/6) \oplus (3,1,-1/3) \oplus (\bar{3},1,4/3) \oplus (1,2,1/2)$, and $5_H = (H_1, T) = (1,2,1/2) \oplus (3,1,-1/3)$ where the field 45 satisfies the following conditions: $(45)^{\alpha\beta}_{\delta} = -(45)^{\beta\alpha}_{\delta}$, $\sum_{\alpha=1}^{5} (45)^{\alpha\beta}_{\alpha} = 0$, and $\upsilon_{45} = \langle 45 \rangle^{15}_{1} = \langle 45 \rangle^{25}_{2} = \langle 45 \rangle^{35}_{3}$. In this model the Yukawa potential for charged fermions reads as:

$$V_Y = 10\,\bar{5}\big(Y_1\, 5^*_H + Y_2\, 45^*_H\big) + 10\,10(Y_3\, 5_H + Y_4\, 45_H) + \text{h.c.}, \tag{1}$$

and the masses for charged leptons and down quarks are given by:

$$M_D = Y_1\, \upsilon^*_5 + 2 Y_2\, \upsilon^*_{45}, \tag{2}$$

$$M_E = Y_1^T\, \upsilon^*_5 - 6 Y_2^T\, \upsilon^*_{45}, \tag{3}$$

where $\langle 5_H \rangle = \upsilon_5$. Y_1 and Y_2 are arbitrary 3×3 matrices. Notice that there are clearly enough parameters in the Yukawa sector to fit all charged fermions masses. See Ref. [15] for the study of the scalar potential and [5] for the relation between the fermion masses at the high scale which is in agreement with the experiment.

There are three different possibilities to generate the neutrino masses [12] at tree level in this context. The model can be extended in three different ways: (i) we can add at least two fermionic $SU(5)$ singlets and generate neutrino masses through the type I seesaw mechanism [9], (ii) we can add a 15 of Higgs and use the type II seesaw [16] mechanism, or (iii) we can generate neutrino masses through the type III [10] and type I seesaw mechanisms adding at least two extra matter fields in the 24 representation [12]. In Ref. [8] it has been realized the possibility to generated the neutrino masses through type III and type I seesaw adding just one extra matter field in 24 and using higher-dimensional operators. Notice that the third possibility mentioned above is very appealing since we do not have to introduce $SU(5)$ singlets or an extra Higgs. If we add an extra Higgs, 15_H, for type II seesaw mechanism the Higgs sector is even more complicated. In this Letter we focus on the possibility to generate the neutrino masses at the renormalizable level through type III and type I seesaw mechanisms.

The predictions coming from the unification of the gauge couplings in a renormalizable $SU(5)$ model where one uses type I or type II seesaw mechanism for neutrino masses were investigated in Ref. [17]. However, a renormalizable grand unified theory based on $SU(5)$ where the neutrino masses are generated through the type III seesaw mechanism has not been proposed and this is our main task. The SM decomposition of the needed extra multiplet for type III seesaw is given by: $24 = (\rho_8, \rho_3, \rho_{(3,2)}, \rho_{(\bar{3},2)}, \rho_0) = (8,1,0) \oplus (1,3,0) \oplus (3,2,-5/6) \oplus (\bar{3},2,5/6) \oplus (1,1,0)$. In our notation

ρ_3 and ρ_0 are the $SU(2)_L$ triplet responsible for type III seesaw and the singlet responsible for type I seesaw, respectively. Since we have introduced an extra Higgs 45_H and an extra matter multiplet 24, the Higgs sector of our model is composed of 5_H, 24_H and 45_H, and the matter is unified in the $\bar{5}$, 10 and 24 representations.

The new relevant interactions for neutrino masses in this context are given by:

$$V_\nu = c_i\, \bar{5}_i\, 24\, 5_H + p_i\, \bar{5}_i\, 24\, 45_H + \text{h.c.} \tag{4}$$

Notice from Eqs. (1) and (4) the possibility to generate all fermion masses, including the neutrino masses, with only two Higgses: 5_H and 45_H. The first term in the above equation has been used in Ref. [12] in the context of SUSY $SU(5)$ and in Ref. [8] in the context of non-SUSY $SU(5)$. Notice that the main difference at this level of our model with the model presented in Ref. [8] is that we do not need to use higher-dimensional operators and with only two Higgses we can generate all fermion masses. Notice that in $SU(5)$ models usually that is not possible.

Using Eq. (4) the neutrino mass matrix reads as:

$$M_{ij}^\nu = \frac{a_i a_j}{M_{\rho_3}} + \frac{b_i b_j}{M_{\rho_0}}, \tag{5}$$

where

$$a_i = c_i v_5 - 3 p_i v_{45}, \tag{6}$$

and

$$b_i = \frac{\sqrt{15}}{2}\left(\frac{c_i v_5}{5} + p_i v_{45}\right). \tag{7}$$

The theory predicts one massless neutrino at tree level. Therefore, we could have a normal neutrino mass hierarchy: $m_1 = 0$, $m_2 = \sqrt{\Delta m_{\text{sun}}^2}$ and $m_3 = \sqrt{\Delta m_{\text{sun}}^2 + \Delta m_{\text{atm}}^2}$ or the inverted neutrino mass hierarchy: $m_3 = 0$, $m_2 = \sqrt{\Delta m_{\text{atm}}^2}$ and $m_1 = \sqrt{\Delta m_{\text{atm}}^2 - \Delta m_{\text{sun}}^2}$. $\Delta m_{\text{sun}}^2 \approx 8 \times 10^{-5}\ \text{eV}^2$ and $\Delta m_{\text{atm}}^2 \approx 2.5 \times 10^{-3}\ \text{eV}^2$ are the mass-squared differences of solar and atmospheric neutrino oscillations [18], respectively.

The masses of the fields responsible for the seesaw mechanisms are computed using the new interactions between 24 and 24_H in this model:

$$V_{24} = m\, \text{Tr}\big(24^2\big) + \lambda\, \text{Tr}\big(24^2 24_H\big). \tag{8}$$

Once 24_H gets the expectation value, $\langle 24_H \rangle = v\, \text{diag}(2, 2, 2, -3, -3)/\sqrt{30}$, the masses of the fields living in 24 are given by:

$$M_{\rho_0} = m - \frac{\tilde{\lambda} M_{\text{GUT}}}{\sqrt{\alpha_{\text{GUT}}}}, \tag{9}$$

$$M_{\rho_3} = m - \frac{3\tilde{\lambda} M_{\text{GUT}}}{\sqrt{\alpha_{\text{GUT}}}}, \tag{10}$$

$$M_{\rho_8} = m + \frac{2\tilde{\lambda} M_{\text{GUT}}}{\sqrt{\alpha_{\text{GUT}}}}, \tag{11}$$

$$M_{\rho_{(3,2)}} = M_{\rho_{(\bar{3},2)}} = m - \frac{\tilde{\lambda} M_{\text{GUT}}}{2\sqrt{\alpha_{\text{GUT}}}}, \tag{12}$$

where we have used the relations $M_V = v\sqrt{5\pi\alpha_{\text{GUT}}/3}$, $\tilde{\lambda} = \lambda/\sqrt{50\pi}$ and chose M_V as the unification scale. Notice that when the fermionic triplet ρ_3, responsible for type III seesaw mechanism, is very light the rest of the fields living in 24 have to be heavy if we do not assume a very small value for the λ parameter.

Before study the unification constraints and discuss the different contributions to proton decay let us summarize our results. We have found that it is possible to write down a renormalizable non-supersymmetric grand unified theory based on the $SU(5)$ gauge symmetry where the neutrino masses are generated through type I and type III seesaw mechanisms using just two Higgses 5_H and 45_H. In this context, as in the model proposed in Ref. [8], the implementation of leptogenesis is possible. However, in their case one could have only resonant leptogenesis. Those issues will be discussed in detail in a future publication.

3. Unification constraints and nucleon decay

In order to understand the constraints coming from the unification of gauge couplings we can use the B-test relations: $B_{23}/B_{12} = 0.716 \pm 0.005$ and $\ln M_{\text{GUT}}/M_Z = (184.9 \pm 0.2)/B_{12}$, where the coefficients $B_{ij} = B_i - B_j$ and $B_i = b_i + \sum_I b_{iI} r_I$ are the so-called effective coefficients. Here b_{iI} are the appropriate one-loop coefficients of the particle I and $r_I = (\ln M_{\text{GUT}}/M_I)/(\ln M_{\text{GUT}}/M_Z)$ $(0 \leqslant r_I \leqslant 1)$ is its "running weight" [19]. To obtain the above expressions we have used the following experimental values at M_Z in the $\overline{\text{MS}}$ scheme [18]: $\sin^2\theta_W(M_Z) = 0.23120 \pm 0.00015$, $\alpha_{\text{em}}^{-1}(M_Z) = 127.906 \pm 0.019$ and $\alpha_s(M_Z) = 0.1176 \pm 0.002$. In the rest of the Letter we will use the central values for input parameters in order to understand the possible predictions coming from the unification of gauge interactions.

As is well known the B-test fails badly in the Standard Model case since $B_{23}^{\text{SM}}/B_{12}^{\text{SM}} = 0.53$, and hence the need for extra light particles with suitable B_{ij} coefficients to bring the value of the B_{23}/B_{12} ratio in agreement with its experimental value. In order to understand this issue we compute and list the B_{ij} coefficients of the different fields in our model in Tables 1–3. Notice that we have chosen the mass of the superheavy gauge bosons as the unification scale. From the tables we see clearly that Σ_3, Φ_3 and ρ_3 fields improve unification with respect to the Standard Model case since those fields have a negative and positive contribution to the coefficients B_{12} and B_{23}, respectively.

Before we study the different scenarios in agreement with the unification of gauge interactions let us discuss the different contributions to proton decay. For a review on proton decay see [20]. In this model there are five multiplets that mediate proton decay. These are the superheavy gauge bosons $V = (3, 2, -5/6) \oplus (\bar{3}, 2, 5/6)$, the $SU(3)$ triplet T, Φ_3, Φ_5 and Φ_6. The least model dependent and usually the dominant proton decay contribution in non-supersymmetric scenarios comes from gauge boson mediation. Its strength is set by M_V and α_{GUT}.

Table 1
Contributions of 5_H, and 24_H multiplets to the B_{ij} coefficients, including the contribution of the Higgs doublet in 45_H. The masses of the Higgs doublets are taken to be at M_Z

	2HSM	T	Σ_8	Σ_3
B_{23}	4	$-\frac{1}{6}r_T$	$-\frac{1}{2}r_{\Sigma_8}$	$\frac{1}{3}r_{\Sigma_3}$
B_{12}	$\frac{36}{5}$	$\frac{1}{15}r_T$	0	$\frac{1}{3}r_{\Sigma_3}$

Table 2
Contributions of the fields in 45_H to the B_{ij} coefficients, excluding the contribution of the Higgs doublet H_2

	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6
B_{23}	$-\frac{2}{3}r_{\Phi_1}$	$-\frac{5}{6}r_{\Phi_2}$	$\frac{3}{2}r_{\Phi_3}$	$\frac{1}{6}r_{\Phi_4}$	$-\frac{1}{6}r_{\Phi_5}$	$-\frac{1}{6}r_{\Phi_6}$
B_{12}	$-\frac{8}{15}r_{\Phi_1}$	$\frac{2}{15}r_{\Phi_2}$	$-\frac{9}{5}r_{\Phi_3}$	$\frac{17}{15}r_{\Phi_4}$	$\frac{1}{15}r_{\Phi_5}$	$\frac{16}{15}r_{\Phi_6}$

Table 3
Extra contributions of the extra matter in the multiplet 24 to B_{ij} coefficients

	ρ_8	ρ_3	$\rho_{(3,2)}$	$\rho_{(\bar{3},2)}$
B_{23}	$-2r_{\rho_8}$	$\frac{4}{3}r_{\rho_3}$	$\frac{1}{3}r_{\rho_{(3,2)}}$	$\frac{1}{3}r_{\rho_{(\bar{3},2)}}$
B_{12}	0	$-\frac{4}{3}r_{\rho_3}$	$\frac{2}{3}r_{\rho_{(3,2)}}$	$\frac{2}{3}r_{\rho_{(\bar{3},2)}}$

Notice that we have identified M_V with the GUT scale, i.e., we set $M_V \equiv M_{\text{GUT}}$. We are clearly interested in the regime where M_V is above the experimentally established bounds set by proton decay, $M_V \gtrsim (2 \times 10^{15})\ 5 \times 10^{13}$ GeV if we do (not) neglect the fermion mixings [21].

In this theory the value of M_{GUT} depends primarily on the masses of Σ_3, ρ_3, Φ_1 and Φ_3 through their negative contributions to the B_{12} coefficient. The Φ_3 field cannot be very light due to proton decay constraints. The Φ_3 contributions to proton decay are coming from interactions $Y_4 Q^T \imath\sigma_2 \Phi_3 Q$ and $Y_2 Q^T \imath\sigma_2 \Phi_3^* L$. The field Φ_3 should be heavier than 10^{11} GeV in order to not conflict experimental data. Of course, this rather naive estimate holds if one assumes most natural values for Yukawa couplings. If for some reasons one of the two couplings is absent or suppressed the bound on Φ_3 would cease to exist. For example, if we choose Y_4 to be an anti-symmetric matrix, the coupling $Y_4 Q^T \imath\sigma_2 \Phi_3 Q$ vanishes. Therefore, Φ_3 could be very light. In general the field Σ_3 could be between the electroweak and the GUT scales, while ρ_3 has to be always below the seesaw scale, $M_{\rho_3} \lesssim 10^{14}$ GeV. Let us study several scenarios where the unification constraints are quite different:

- The first scenario corresponds to the case when Σ_3 is at GUT scale, while Φ_3 and/or ρ_3 could be below the unification scale. The rest of the fields are at the unification scale. Using the B_{ij} coefficients listed in Tables 1–3 we find that if Φ_3 is at GUT scale it is possible to achieve unification at 1.83×10^{14} GeV if $M_{\rho_3} = 1.13 \times 10^8$ GeV. However, if ρ_3 is at the seesaw scale, 10^{14} GeV, we achieve unification at 2.46×10^{14} GeV if $M_{\Phi_3} = 3.68 \times 10^9$ GeV. In both cases the unification scale is rather low and it is possible to achieve unification with only one of these fields, Φ_3 or ρ_3, since in this model one can have two light Higgs doublets at M_Z. Notice that in the first case we have to suppress the gauge contributions to nucleon decay, while in the second case both the Φ_3 and gauge contributions have to be suppressed in order to satisfy the experimental bounds on proton decay lifetimes, typically $\tau_p^{\text{exp}} \gtrsim 10^{33}$ years.
- In the second scenario Σ_3 is at the electroweak scale. In this case if Φ_3 is at the GUT scale and $M_{\rho_3} = 1.35 \times 10^{11}$ GeV the gauge couplings unify at 1.83×10^{14} GeV. Now, in the case when ρ_3 is at the seesaw scale the unification is at 2.11×10^{14} GeV if $M_{\Phi_3} = 1.01 \times 10^{12}$ GeV. Notice that as in the previous scenario the unification scale is very low, while the mass of Φ_3 is always above the lower bound coming from nucleon decay. Therefore, we only have to suppress the gauge contributions to proton decay through the fermionic mixings [21].
- In the previous scenarios we have assumed that the fields Φ_3, ρ_3 and Σ_3 could be below the GUT scale, while the rest of the fields are at the unification scale. Now let us analyze the case when those fields can contribute to the running of gauge couplings. In particular the contributions of Φ_1 and Σ_8 are quite relevant in order to understand what is the maximal unification scale in our model. Notice that Φ_1 has negative contributions to the B_{23} and B_{12} coefficients, while Σ_8 has only negative contribution to B_{23}. When those fields, Φ_1 and Σ_8, are very light the unification scale will be higher than in the previous scenarios since in this case the rest of the fields have to be lighter in order to satisfy the B-test relations. It is easy to understand that the maximal unification scale in this scenario corresponds to the case when $M_{\Phi_1} = M_{\Sigma_8} = M_Z$, $M_{\Sigma_3} = M_{\text{GUT}}$, $M_{\Phi_3} = 1.2 \times 10^9$ GeV and $M_{\rho_3} = 10^{14}$ GeV. In this case the unification scale is $M_{\text{GUT}} = 1.2 \times 10^{17}$ GeV. Therefore, in this case one can conclude that there is no hope to test this scenario at future proton decay experiments since $\tau_p \gtrsim 10^{41}$ years.

It is important to know which is the minimal value for the mass of the fermionic triplet, responsible for type III seesaw, consistent with unification. The minimal value of M_{ρ_3} corresponds to the case when Σ_3 and Φ_3 are at the GUT scale, while Φ_1 and Σ_8 are close to the electroweak scale. In this case $M_{\rho_3} \approx 1.5$ TeV and the unification scale is 3×10^{16} GeV. Therefore, we can conclude that in this case the seesaw mechanism could be tested at future collider experiments. The minimal value of M_{Φ_3} in our model is 5×10^8 GeV when $M_{\Phi_1} = M_{\Sigma_8} \approx M_Z$, $M_{\Sigma_3} \approx M_{\text{GUT}} \approx 5 \times 10^{16}$ GeV and $M_{\rho_3} = 10^{14}$ GeV. Notice that in all the scenarios studied in this section we can satisfy the constraints coming from proton decay and neutrino masses.

The theory proposed in this Letter can be considered as the renormalizable version of the theory given in Ref. [8]. As we have discussed in this Letter, the predictions coming from proton decay, the unification constraints and leptogenesis are quite different in this case. Our theory can be considered as the simplest renormalizable grand unified theory based on the $SU(5)$ gauge symmetry.

4. Summary

We have investigated the possibility to find the simplest renormalizable grand unified theory based on the $SU(5)$ gauge symmetry. We find that it is possible to generate all fermion masses with only two Higgs bosons, 5_H and 45_H. In this context the neutrino masses are generated through the type III and type I seesaw mechanisms. The predictions coming from the unification of gauge couplings and the stability of the proton have been discussed in detail. In this theory the leptogenesis mechanism can be realized through the out of equilibrium decays of the fermions ρ_3 and ρ_0 in the adjoint representation. We refer to this theory as "renormalizable adjoint $SU(5)$".

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