Low-scale baryogenesis from three-body decays

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Baryogenesis at the TeV scale from CP-violating decays of a massive particle requires some way to avoid the washouts from processes closely related to the existence of CP violation. Baryogenesis from three-body decays (instead of two-body decays) has been proposed as a way for TeV scale baryogenesis. In this work we revisit this statement and show that, although three-body-decay models can provide interesting alternatives to address other kind of difficulties faced by low-scale baryogenesis, the generic problem due to the washouts proportional to the CP asymmetry persists. Therefore, as in two-body-decay models, the mass of the decaying particle cannot be below ~ 10 TeV unless some mechanism to avoid these kinds of washouts is implemented.

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I. INTRODUCTION

Models for explaining the baryon asymmetry of the universe via the CP-violating decay of heavy particles typically involve high energy scales. Two kinds of problems can be identified for low-scale baryogenesis (below $\sim 10^4$ GeV). On one hand, the parameters of a given model may be constrained by issues not related to baryogenesis. In turn, these constraints may imply bounds for other parameters which are key to baryogenesis, like decay widths or the CP asymmetry. A notable example arises from the connection with light neutrino masses in some leptogenesis models, like the Davidson-Ibarra bound [1] on the CP asymmetry for type-I leptogenesis with hierarchical heavy neutrino masses, which implies a lower bound on the mass M of the decaying particle for successful baryogenesis, namely $M \gtrsim 10^8$–10^9 GeV (see Ref. [2] for a detailed analysis). Also, the amount of hierarchy allowed for couplings of the same kind may restrict the scale of baryogenesis, because the out-of-equilibrium decay condition typically requires tiny couplings to be satisfied at low temperatures, while enough CP violation may require the existence of another particle species with the same quantum numbers and much larger couplings (see, e.g., the discussion in [3]).

On the other hand, there is another problem which is intrinsic to all models of baryogenesis from particle decays and arises from the washout processes related to the absorptive part of one-loop contributions to the CP asymmetry in decays. The strength of these processes is tied to the value of the CP asymmetry and their washout effect increases as the temperature during baryogenesis decreases (because the expansion rate of the universe becomes milder). It has been shown that this typically implies $M \gtrsim 10^5$ GeV for successful baryogenesis (see, e.g., [4]).

Masses as high as those given above might bring hierarchy problems [5,6], be incompatible with cosmological scenarios that require low reheating temperatures, and, more importantly, preclude experimental exploration in the foreseeable future. All this motivates research on baryogenesis models at or below the TeV scale (see, e.g., the review [7]), including ways to avoid the problems mentioned before for thermal baryogenesis from particle decays.

For standard cosmological scenarios, with thermal baryogenesis occurring in a radiation dominated universe, three well-known ways (or mechanisms) have been identified and implemented in numerous models to prevent too much washout from the processes closely related to the CP asymmetry, namely: (i) Enhancement of the CP asymmetry due to quasidegenerate particles. This requires at least two

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particles with the same quantum numbers and very similar masses (according to the level of degeneracy oscillations may or may not be relevant in this case). (ii) Avoidance of washouts due to late decays, i.e., the particles decay and generate the asymmetry at temperatures well below M, when the rate of the washout processes has fallen to nondangerous values. In this mechanism, the decay width must be tiny, therefore inverse decays and related production processes involving the decay couplings are suppressed, imposing the need for another interaction to produce the particles in the first place. Moreover, this new interaction must not be active at temperatures around or below M if it can contribute to the depletion of the particles so that the CP-violating late decays indeed occur. Finally, note that all this also implies that the final asymmetry is directly proportional to the abundance of the heavy particles at the beginning of the baryogenesis epoch (that might be thermal or not, depending on the production mechanism), which results in a significant dependence on initial conditions. (iii) Boltzmann suppression of washouts when some of the decay products are massive (so that all relevant washout processes become Boltzmann suppressed). For baryogenesis above the electroweak phase transition this calls for the introduction of new fields (apart from the decaying particle that generates the asymmetry) and there is also another more subtle requirement discussed in [4]. A detailed joint discussion of these three mechanisms can be found in [4]. We would also like to note that for very light decaying particles (M around 100 GeV or below) (ii) and (iii) must be combined in order to avoid washouts (see the recent analysis of washouts in postsphaleron baryogenesis in [8]).

In addition other ways have been proposed, particularly the one we are interested to analyze in this work, which is baryogenesis via three-body decays (instead of two-body decays), set forth in [3] and implemented, e.g., in [9,10] (see also [11], [12] for a previous three-body-decay model, [13] for another proposal, and [14] for nonstandard cosmological scenarios). Our aim is to show that, although three-body-decay models may alleviate or solve the first kinds of problems mentioned above, they do not provide an alternative to (i), (ii), or (iii) for solving the crucial problem from washouts proportional to the CP asymmetry. In this regard two- and three-body-decay models are (almost) equivalent and for both classes of models M cannot be below $\sim 10^4$ GeV, unless they resort to one of the ways specified above, i.e., (i), (ii), or (iii), to avoid too much washout from the scattering processes closely related to the CP asymmetry. In order to perform a detailed discussion we introduce a scalar model in Sec. II to realize baryogenesis from three-body decays. Then, in Sec. III, we set the Boltzmann equations (BEs) and discuss the similarities and differences of the lower bound on M compared to two-body-decay models. Finally, we summarize our conclusions in Sec. IV.

II. A MODEL FOR BARYOGENESIS FROM THREE-BODY DECAYS

The possibility to realize baryogenesis at the TeV scale from CP-violating three-body decays was suggested in [3]. In the model proposed in [3] as an illustration, all the operators in the Lagrangian that are relevant for baryogenesis involve three fields and the absorptive parts of the one-loop diagrams contributing to the CP asymmetry involve $2 \to 2$ processes, which can washout the asymmetry very efficiently. For this class of three-body-decay models the analysis performed in [4] can be applied more directly than in the model we will introduce below, because in the numerical scans of [4] the decay width is a free parameter allowed to take any value (covering, in particular, the naturally small values that are expected in three-body decays) and the relation between CP asymmetry and washouts is quite similar (which can be verified by identifying the couplings and masses of the scalar singlets in [3] with the couplings and mass of the Majorana neutrino in the propagators of [4]).

That being said, there are two differences that may be relevant for our discussion. On one hand, the propagators of scalar and Majorana fields are different and consequently the washout rates have different dependence on the temperature (T), which is more significant for $T \ll M$. On the other hand, in three-body-decay models the same interactions responsible for decays and inverse decays imply the

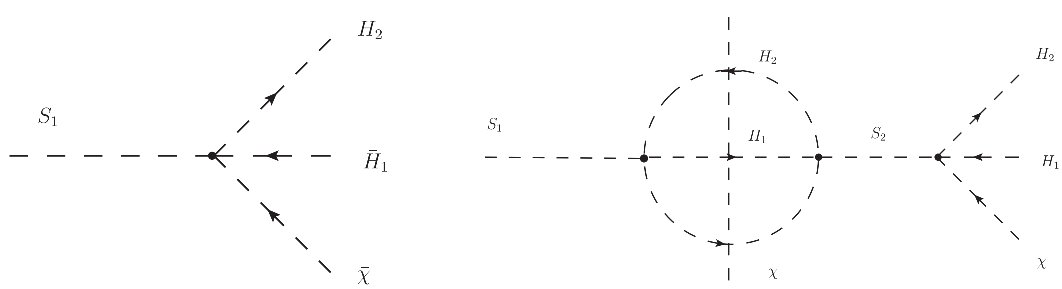

FIG. 1. Interference of the tree-level diagram on the left and the one-loop diagram on the right can give rise to a CP asymmetry in the decays of S_1. The CP-odd phase arises when $\mathrm{Im}[(\lambda_1\lambda_2^*)^2] \neq 0$, while the CP-even phase arises when all the particles along the cut in the one-loop diagram can be on shell. The process at the right of the cut may induce very efficient washouts at low temperatures and is responsible for the lower bound on M_1 discussed in this paper.

TABLE I. Charges of the fields under the exotic Z_2 and $U(1)$ symmetries. Depending on the choice of Z_2-charges for H_2 and χ it is possible to have different possibilities for the lightest stable exotic particle(s), but we are not interested in analyzing this issue and any option is useful for our purposes. Here "SM" represents all SM fields.

	Z_2	$U(1)$
SM	$+1$	0
$S_{1,2}$	-1	0
H_2	-1 $(+1)$	1
χ	$+1$ (-1)	1

existence of $2 \to 2$ scattering processes which increase the production rate of the heavy particles at $T \gtrsim M$.

Motivated by the above considerations and in order to perform a detailed numerical analysis, we build a scalar three-body-decay model where all processes relevant for baryogenesis involve more particles than in standard baryogenesis from particle decays, and consequently they are all phase-space suppressed. In particular, we want only $3 \to 3$ processes to appear at the right of the cut in the one-loop diagrams, see Fig. 1.

As a way of accomplishing this we consider an extension of the Standard Model (SM) with a second Higgs doublet, H_2, two real scalar singlets, S_i $(i = 1, 2)$, and a complex scalar singlet field, χ. In order to forbid two-body decays for the S_i, the model is supplemented with a discrete symmetry Z_2 and another exotic symmetry which can be a different discrete symmetry or a global $U(1)$. The charge assignments are given in Table I. We stress that our intention is not to propose a realistic model for baryogenesis, but to test the idea of three-body decays as a way for TeV scale baryogenesis, as explained above. Therefore we will not study issues like the vacuum stability of the scalar potential, breaking of the symmetries, or the possibility to have a dark matter candidate [although the charges can be assigned in order to choose different possibilities for the lightest stable exotic particle(s)]. The relevant terms for baryogenesis in the scalar potential V are

$$V(H_1, H_2, S_i, \chi) = \sum_i \frac{1}{2} M_i^2 S_i^2 + m_\chi^2 \chi^\dagger \chi + m_{H_2}^2 H_2^\dagger H_2 + \sum_i \lambda_i S_i H_2^\dagger H_1 \chi + \text{H.c.} + \dots, \quad (1)$$

where H_1 is the SM Higgs.

Baryogenesis occurs through "split Higgsogenesis" [15]: an asymmetry initially develops in the scalar sector due to the CP-violating decays of the lightest real scalar singlet, $S_1 \to H_2 \bar{H}_1 \bar{\chi} (\bar{H}_2 H_1 \chi)$, and then it is partially transferred to baryons via fast Yukawa and sphaleron processes. In the following section we give a set of appropriate BEs and make a scan over the relevant parameters to determine the lowest value of M_1 that allows for successful baryogenesis without implementing any of the three mechanisms described in the introduction.

III. MASS BOUNDS FOR BARYOGENESIS FROM THREE-BODY DECAYS

Using Maxwell-Boltzmann statistics, assuming kinetic equilibrium, and working at linear order in the asymmetries, baryogenesis in the model presented in the previous section can be described with the following set of transport equations:

$$\frac{\mathrm{d}Y_{S_1}}{\mathrm{d}z} = -\frac{1}{zHs} \left(\frac{Y_{S_1}}{Y_{S_1}^{\mathrm{eq}}} - 1 \right) (\gamma_D + \gamma_{\mathrm{scat}}),$$
$$\frac{\mathrm{d}Y_{\Delta H_2}}{\mathrm{d}z} = \frac{1}{zHs} \left\{ \epsilon \left(\frac{Y_{S_1}}{Y_{S_1}^{\mathrm{eq}}} - 1 \right) (\gamma_D + \gamma_{\mathrm{scat}}) - (y_{H_2} - y_{H_1} - y_\chi) \times \left[2\gamma_6 + \frac{\gamma_D}{2} + \left(\frac{Y_{S_1}}{Y_{S_1}^{\mathrm{eq}}} + 2 \right) \frac{\gamma_{\mathrm{scat}}}{6} \right] \right\}, \quad (2)$$

where we have used the notation H for the Hubble rate, $z \equiv M_1/T$ (with T denoting the temperature), $Y_a \equiv \frac{n_a}{s}$ (with n_a being the number density of the particle specie "a", and s being the entropy density), $Y_{\Delta a} \equiv Y_a - Y_{\bar{a}}$ (with $\bar{a}$ denoting the CP-conjugate of a), and $y_a \equiv Y_{\Delta a}/Y_a^{\mathrm{eq}}$ (with Y_a^{eq} being the equilibrium number density corresponding to one degree of freedom of particle "a", normalized to the entropy density).

Since we want to determine the lowest value of M_1 compatible with successful baryogenesis without implementing any of the known mechanisms described in the introduction that allow for $M_1 \sim$ few TeV, i.e., without resorting to quasidegenerate states or massive decay products, we take $M_2 \gg M_1 \gg m_{H2}, m_\chi$. Then, at lowest nonzero order in M_1/M_2, the CP asymmetry in the decays of S_1, arising from the interference of tree-level and one-loop diagrams, like the one depicted in Fig. 1, is given by

$$\epsilon \equiv \frac{\gamma(S_1 \to H_2 \bar{H}_1 \bar{\chi}) - \gamma(S_1 \to \bar{H}_2 H_1 \chi)}{\gamma(S_1 \to H_2 \bar{H}_1 \bar{\chi}) + \gamma(S_1 \to \bar{H}_2 H_1 \chi)} = -\frac{3}{2^7 \pi^3} \frac{\mathrm{Im}[(\lambda_1 \lambda_2^*)^2]}{|\lambda_1|^2} \frac{M_1^2}{M_2^2}. \quad (3)$$

When the relative phase of the couplings λ_1 and λ_2 is equal to $-\pi/4$, the CP asymmetry has a maximum value equal to

$$\epsilon^{\max} = \frac{3}{2^7 \pi^3} |\lambda_2|^2 \frac{M_1^2}{M_2^2} = \frac{3}{2^7 \pi^3} \tilde{\lambda}^2, \quad (4)$$

where we have defined the dimensionless parameter $\tilde{\lambda} \equiv \frac{|\lambda_2|}{M_2/M_1}$. Finally, for $M_2 \gg M_1 \gg m_{H2}, m_\chi$, the three reaction densities in these BEs are given at tree level by

$$\gamma_D = \frac{1}{2^7\pi^3}\frac{K_1(z)}{K_2(z)} n_{S_1}^{\rm eq} \frac{M_1^2}{v^2}\tilde{m}, \tag{5}$$

$$\gamma_{\rm scat} = \frac{3}{(2\pi)^5}\tilde{m} v^{-2} M_1^5 z^{-3} K_1(z), \tag{6}$$

$$\gamma_6 = \frac{254}{(2\pi)^9}\tilde{\lambda}^4 M_1^4 z^{-8}, \tag{7}$$

whose magnitudes depend on two parameters that we have defined for convenience as $\tilde{m} \equiv \frac{(|\lambda_1| v)^2}{M_1}$ (with v denoting the Higgs vacuum expectation value, $v \simeq 174$ GeV) and $\tilde{\lambda}$ (introduced before). While γ_D is just the reaction density of the decays of S_1, i.e., the total number of decays per unit time and volume (calculated at tree level and therefore equal to the inverse decays rate per unit volume), $\gamma_{\rm scat}$ and γ_6 are the sum of reaction densities of several processes with a similar role in baryogenesis and they consequently appear together in the BEs. In $\gamma_{\rm scat}$ we have summed the reaction densities of all $2 \to 2$ scatterings involving S_1 in the initial state, i.e., of $S_1\chi \to \bar{H}_1 H_2$ and all processes obtained by CP conjugation and/or interchanging initial and final states. Furthermore, γ_6 includes the reaction densities of all $3 \leftrightarrow 3$ and $2 \leftrightarrow 4$ processes mediated by S_2, i.e., the one at the right of the cut in Fig. 1 and related processes obtained by CP conjugation and/or interchanging some of the initial and final states. All of these processes tend to washout the asymmetry and the tight connection between the magnitudes of $\epsilon^{\rm max}$ and γ_6 is responsible for the lower bound on M_1 that we are going to calculate.

The BEs (2) can be complemented by a set of relations among chemical potentials and density asymmetries due to fast interactions and conserved charges, which lead to the equations

$$\begin{aligned} y_\chi &= -2 y_{H_2}, \\ y_{H_1} &= -\frac{13}{79} y_{H_2}, \\ Y_B &= \frac{6}{79} Y_{\Delta H_2}, \end{aligned} \tag{8}$$

with the first two equations allowing us to solve the BEs for $Y_{\Delta H_2}$ and the last one giving the relation between the asymmetry in H_2 and the baryon asymmetry normalized to the entropy density (see Ref. [15]).

Next we proceed to determine the maximum amount of asymmetry that can be generated in the H_2 field as a function of M_1, i.e., we maximize the final value of $Y_{\Delta H_2}$ over the two free parameters $\tilde{\lambda}$ and $\tilde{m}$ for each value of M_1. In order to achieve this, we integrate the BEs (2), taking $\epsilon = \epsilon^{\rm max}$ and $Y_{\Delta H_2}(z \ll 1) = Y_{S_1}(z \ll 1) = 0$ as initial conditions. Note that we take an initial zero abundance for S_1 because we do not want to study the lower bound on M_1 in scenarios where the S_1 could have been produced by other (CP-conserving) processes, since in this case it is known that M_1 can be in the TeV scale [via the mechanism (ii) described in the introduction]. The result is represented by the thick solid red line in Fig. 2. Taking into account the relation between $Y_{\Delta H_2}$ and Y_B given in Eq. (8), we conclude that the lower bound on M_1 for successful baryogenesis in this model is very high, $M_1 \gtrsim 10^7$ GeV. This is actually much higher than the lower bound $M \sim 10^5$ GeV found in [4] for two-body decays [without the implementation of the mechanisms (i)—(iii) outlined in the introduction]. Also note that the maximum value of $Y_{\Delta H_2}$ grows as the square root of M_1 (see Ref. [4] for a more detailed discussion on parameter dependences in two-body-decay models).

The reason for the higher bound on M_1 compared to the two-body-decay scenario is twofold. On one hand, in the particular model we have chosen, the asymmetry generated in decays originates in the scalar sector, particularly in H_2, and is partially transferred and shared among many fields. Therefore the conversion factor between $Y_{\Delta H_2}$ and Y_B is significantly smaller (around four to five times smaller) than the corresponding conversion factor in more standard baryogenesis-via-leptogenesis models. However, even if this conversion factor were as big as in leptogenesis models ($\sim 1/3$), the lower bound on M_1 would still be well above

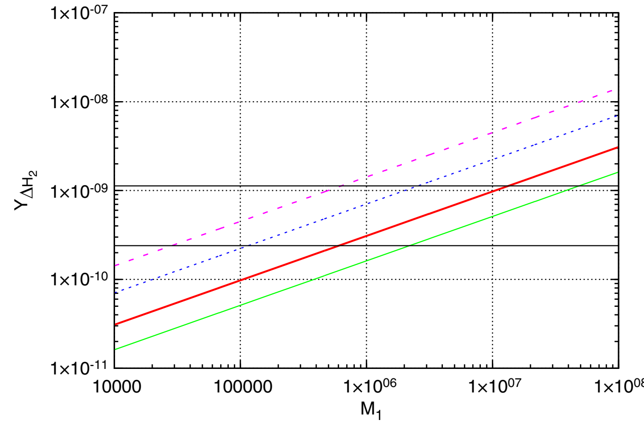

FIG. 2. Maximum H_2 asymmetry as a function of M_1 (in GeV). The solid thick red line gives the asymmetry for the model considered in this paper, the solid thin green line corresponds to the same model but without including the $2 \to 2$ scatterings, i.e., setting $\gamma_{\rm scat} = 0$ in the BEs (see discussion in the text), and the pink-dashed (blue-dotted) line gives the asymmetry for a toy scenario where there is only one process and channel contributing to the CP asymmetry and the washouts mediated by S_2, including (not including) the $2 \to 2$ scatterings. The upper horizontal solid black line indicates the value $Y_{\Delta H_2}$ must have to obtain the observed baryon asymmetry in our model, while the lower horizontal one indicates the value it should have were the conversion factor between Y_B and $Y_{\Delta H_2}$ equal to $28/79$ instead of $6/79$ (drawn to ease comparisons with more standard leptogenesis models).

10^5 GeV (the two horizontal solid black lines in Fig. 2 correspond to the values $Y_{\Delta H_2}$ must have so that the baryon asymmetry equals the observed value, $Y_B^{\rm obs} \simeq 8.6 \times 10^{-11}$, for conversion factors equal to 6/79 and 28/79). On the other hand, the four-field operators allow for many $3 \leftrightarrow 3$ and $2 \leftrightarrow 4$ washout processes, with several channels contributing to each of them, resulting in an enhancement of the washout rate relative to the *CP* asymmetry when compared to two-body-decay scenarios. In order to quantify this effect, in Fig. 2 we have also plotted the maximum value of $Y_{\Delta H_2}$ that would be obtained if only one process and channel contributed to the *CP* asymmetry and the related washout rate γ_6 (see the pink-dashed line). Again it can be seen that, even in this toy scenario, the lower bound on M_1 is well above 10^5 GeV (or 10^4 GeV for a larger conversion factor), reinforcing the conclusion that the three-body-decay mechanism *per se* does not allow for baryogenesis with M_1 at the TeV scale.

As noted in the previous section, one of the differences of three-body-decay models compared to two-body decays is that the same operators in the Lagrangian that are responsible for the three-body decays also grant $2 \to 2$ scattering processes, which are much more efficient than inverse decays ($H_2\bar{H}_1\bar{\chi}, \bar{H}_2H\chi \to S_1$) at producing the S_1 at high temperatures (while becoming subdominant at temperatures somewhat below M_1). This may allow us to choose smaller values of λ_1 to delay the decays (reducing washout effects on the asymmetry) without compromising too much the production of S_1, and, consequently, realizing a late decay scenario without the need for an extra interaction to produce S_1 at high temperatures [see (ii) in the introduction]. Indeed this is a relevant effect, although, as we have stated above, the bound on M_1 stays above 10^4 GeV. To demonstrate this point we have drawn the solid thin green line in Fig. 2, which gives the maximum value of $Y_{\Delta H_2}$ without including the $2 \to 2$ scattering processes in the BEs (i.e., taking $\gamma_{\rm scat} = 0$). It can be seen that if it were not for this effect the lower bound on M_1 would be a factor of 3 to 4 larger than quoted previously (for comparisons we have also depicted with the blue-dotted line the maximum value of $Y_{\Delta H_2}$ taking $\gamma_{\rm scat} = 0$ in the toy scenario with only one process and channel contributing to the *CP* asymmetry and the related washout rate).

Before concluding we wish to make one more remark. For simplicity (considering in particular the large number of processes involved), we have worked in the hierarchical limit $M_2 \gg M_1$. According to the analysis of [4] for a two-body-decay model, the bound on M_1 could be somewhat lower for $M_2 \sim 5$–$10M_1$. However the difference with respect to the hierarchical limit is mild (less than a factor of 2 for the inert doublet model studied in [4]), which does not alter the conclusion of this work (moreover, note that to find the bound when M_2 is closer to M_1 would require us to include the evolution of Y_{S_2} in the BEs, together with processes with S_2 on shell).

IV. CONCLUSIONS

Baryogenesis from particle decays can be realized in a host of models beyond the SM of particle physics. For the reasons explained in the introduction, typically the mass M of the decaying particle must be very high, $M \gtrsim 10^4$–10^5 GeV, or even much larger. However, there are theoretical and experimental motivations to explore models with lower masses, at the TeV scale or below. Baryogenesis from three-body decays (instead of two-body decays) has been proposed as a mechanism for generating the matter-antimatter asymmetry at such low scales. Although three-body-decay models may solve some of the issues mentioned in the introduction, allowing in particular to satisfy the out-of-equilibrium decay condition with larger couplings and to build different neutrino mass models without constraints like the Davidson-Ibarra bound [3,10], in this work we have shown that the general problem posed by the washouts proportional to the *CP* asymmetry is akin to two-body-decay models. That is to say, as in two-body-decay models, these washouts enforce a lower bound $M \gtrsim 10^4$ GeV, unless one of the three ways to avoid them, labeled (i)—(iii) in the introduction, is implemented. It is worth noticing that the mechanism (ii), which requires long lifetimes, might be realized more naturally in three-body-decay models (as compared to two-body decays), but the trade-off is the same: inverse decays and the related scattering processes cannot produce enough particles. Therefore a different production process must be assumed which, in general, implies less predictability, although the common assumption of a thermal population at the beginning of baryogenesis stands out as a possibility to realize low-scale baryogenesis in this case, since it can be accomplished by any fast interaction involving the particles at higher temperatures. These considerations can be useful for model building and interpretation.

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