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Intrinsic deviation from the tri-bimaximal neutrino mixing in a class of A_4 flavor models

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ABSTRACT

It is well known that the tri-bimaximal neutrino mixing pattern V_0 can be derived from a class of flavor models with the non-Abelian A_4 symmetry. We point out that small corrections to V_0, which are inherent in the A_4 models and arise from both the charged-lepton and neutrino sectors, have been omitted in the previous works. We show that such corrections may lead the 3×3 neutrino mixing matrix V to a non-unitary deviation from V_0, but they cannot result in a nonzero value of θ_{13} or any new CP-violating phases. Current experimental constraints on the unitarity of V allow us to constrain the model parameters to some extent.

1. Introduction

Thanks to a number of convincing neutrino oscillation experiments [1], we have known two neutrino mass-squared differences (Δm^2_{21} and $|\Delta m^2_{31}|$) and two neutrino mixing angles (θ_{12} and θ_{23}) to a good degree of accuracy [2]. The smallest neutrino mixing angle θ_{13} remains unknown, but there are some preliminary hints that it might not be very small (e.g., $\theta_{13} \sim 7^\circ$ [2–4]). Nevertheless, current experimental data are consistent very well with a constant neutrino mixing matrix—the so-called tri-bimaximal mixing pattern [5]

$$V_0 = U^T_\omega U^*_\nu = \frac{1}{\sqrt{6}} Q_l \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix} Q_\nu, \tag{1}$$

where

$$U_\omega = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix},$$
$$U_\nu = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & -1 \\ 0 & \sqrt{2} & 0 \\ 1 & 0 & 1 \end{pmatrix}, \tag{2}$$

$\omega = e^{i2\pi/3}$, $Q_l = \mathrm{Diag}\{1, \omega, -\omega^2\}$ and $Q_\nu = \mathrm{Diag}\{1, 1, i\}$ [6]. The diagonal phase matrix Q_l can be rotated away by redefining the phases of three charged-lepton fields, but Q_ν may affect the neutrinoless double-beta decay if neutrinos are the Majorana particles. Given the standard parametrization of the Maki–Nakagawa–Sakata–Pontecorvo (MNSP) neutrino mixing matrix [7], V_0 corresponds to $\theta_{12} = \arctan(1/\sqrt{2}) \approx 35.3^\circ$, $\theta_{13} = 0^\circ$ and $\theta_{23} = 45^\circ$. A more realistic form of the MNSP matrix V is expected to slightly deviate from V_0 due to some nontrivial perturbations, such that both nonzero θ_{13} and CP violation can emerge.

It is possible to derive the tri-bimaximal mixing pattern V_0 from some neutrino mass models with certain flavor symmetries [8]. In this connection the earliest and most popular application is the non-Abelian discrete A_4 symmetry (see, e.g., Refs. [9–11]). But the neutrino mixing matrix derived from a specific A_4 model is in general not equal to V_0 unless some approximations are made. In other words, small corrections to V_0 are generally inherent in the A_4 models and can arise both from the charged-lepton sector and from the neutrino sector. This observation is particularly interesting for an A_4 model built in the vicinity of the TeV scale, because the resultant corrections to V_0 may not be strongly suppressed. We show that such corrections can lead the 3×3 neutrino mixing matrix V to a non-unitary deviation from V_0, although they cannot give rise to a nonzero value of θ_{13} or any new CP-violating phases. We find that current experimental constraints on the unitarity of V allow us to constrain the parameters of an A_4 model to some extent.

The remaining part of this Letter is organized as follows. In Section 2 we first outline the salient features of a typical A_4 model and then diagonalize the 6×6 mass matrices of charged leptons and neutrinos. We show that both U_ω and U_ν in Eq. (2) get modified in this framework. In Section 3 we work out the non-

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Table 1
The particle content and charge assignments of the model [11], where the subscript i (for $i = 1, 2, 3$) stands for the family index.

	Q_i	d_i^c	u_i^c	L_i	$e_1^c,\ e_2^c,\ e_3^c$	ν_i^c	E_i	E_i^c	H_u	H_d	χ_i	χ_i'	$S_{a,b}$
$SU(2)_L$	2	1	1	2	1	1	1	1	2	2	1	1	1
$U(1)_Y$	1/3	2/3	−4/3	−1	2	0	−2	2	1	−1	0	0	0
A_4	1	1	1	3	$1, 1', 1''$	3	3	3	1	1	3	3	1
Z_4	1	1	0	1	3	0	1	1	1	0	2	2	2
Z_3	1	2	0	0	0	1	0	0	2	0	0	1	1

unitary departure of the resultant 3×3 MNSP matrix V from the tri-bimaximal mixing pattern $V_0 = U_\omega^T U_\nu^*$. We also constrain the model parameters to some extent by taking account of current experimental constraints on the unitarity of V. Section 4 is devoted to a summary and some concluding remarks.

2. Corrections to U_ω and U_ν in a typical A_4 model

Let us consider a simple but typical A_4 model proposed by Babu and He in Ref. [11]. The model is an extension of the standard electroweak $SU(2)_L \times U(1)_Y$ model with some additional particles, and it is supersymmetric and $(A_4 \times Z_4 \times Z_3)$-invariant. The particle content and charge assignments are summarized in Table 1. The discrete symmetries force the superpotentials of quarks and leptons to have the following forms:

$$\begin{aligned}
W_q &= y_{ij}^d Q_i d_j^c H_d + y_{ij}^u Q_i u_j^c H_u, \\
W_\ell &= M_E E_i E_i^c + f_\ell L_i E_i^c H_d + h_e (E_1\chi_1 + E_2\chi_2 + E_3\chi_3) e_1^c \\
&\quad + h_\mu (E_1\chi_1 + \omega E_2\chi_2 + \omega^2 E_3\chi_3) e_2^c \\
&\quad + h_\tau (E_1\chi_1 + \omega^2 E_2\chi_2 + \omega E_3\chi_3) e_3^c, \\
W_\nu &= f_\nu L_i \nu_i^c H_u + \frac{1}{2} f_{S_a} \nu_i^c \nu_i^c S_a + \frac{1}{2} f_{S_b} \nu_i^c \nu_i^c S_b \\
&\quad + \frac{1}{2} f_{\chi'} \big[(\nu_2^c \nu_3^c + \nu_3^c \nu_2^c) \chi_1' + (\nu_1^c \nu_3^c + \nu_3^c \nu_1^c) \chi_2' \\
&\quad + (\nu_2^c \nu_1^c + \nu_1^c \nu_2^c) \chi_3' \big],
\end{aligned} \tag{3}$$

where the notations are self-explanatory [11]. Note that the quark sector is completely the same as that in the minimal supersymmetric standard model, and the Z_4 symmetry works as an R-parity such that the superpotentials possess two units of charge. Thanks to the supersymmetry and new scalars in Eq. (3), it is possible to obtain the vacuum expectation values [11]

$$\begin{aligned}
&\langle S_a \rangle = 0, \qquad \langle S_b \rangle = v_s, \qquad \langle H_u \rangle = v_u, \qquad \langle H_d \rangle = v_d, \\
&\langle \chi \rangle = (v_\chi, v_\chi, v_\chi), \qquad \langle \chi' \rangle = (0, v_{\chi'}, 0),
\end{aligned} \tag{4}$$

where $v_u^2 + v_d^2 = v^2$ with $v \simeq 174$ GeV. Thus the A_4 symmetry is broken after χ and χ' develop their vacuum expectation values.

In the basis of (e, E) versus $(e^c, E^c)^T$, we obtain the 6×6 mass matrix of charged leptons from Eqs. (3) and (4):

$$\mathcal{M}_{\ell E} = \begin{pmatrix} \mathbf{0} & f_\ell v_d \mathbf{1} \\ H & M_E \mathbf{1} \end{pmatrix}, \tag{5}$$

where $\mathbf{1}$ denotes the 3×3 identity matrix, and

$$H = \begin{pmatrix} h_e & h_\mu & h_\tau \\ h_e & \omega h_\mu & \omega^2 h_\tau \\ h_e & \omega^2 h_\mu & \omega h_\tau \end{pmatrix} v_\chi = \sqrt{3}\, U_\omega \begin{pmatrix} h_e & 0 & 0 \\ 0 & h_\mu & 0 \\ 0 & 0 & h_\tau \end{pmatrix} v_\chi. \tag{6}$$

Note that f_ℓ, M_E and h_α (for $\alpha = e, \mu, \tau$) can all be arranged to be real in a suitable phase convention, and the mass scale M_E is assumed to be extremely large in comparison with the magnitudes of $f_\ell v_d$ and $h_\alpha v_\chi$. The 6×6 Hermitian matrix $\mathcal{M}_{\ell E} \mathcal{M}_{\ell E}^\dagger$ can be diagonalized via the unitary transformation $V_l^\dagger \mathcal{M}_{\ell E} \mathcal{M}_{\ell E}^\dagger V_l$, where V_l is given by

$$V_l \simeq \begin{pmatrix} \mathbf{1} + \frac{HH^\dagger}{M_E^2} & \frac{f_\ell v_d}{M_E} \mathbf{1} \\ -\frac{f_\ell v_d}{M_E} \mathbf{1} & \mathbf{1} + \frac{HH^\dagger}{M_E^2} \end{pmatrix} \begin{pmatrix} U_\omega & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} \tag{7}$$

as a good approximation. The masses of three standard charged leptons turn out to be

$$m_\alpha \simeq \sqrt{3}\, \frac{f_\ell v_d}{M_E} v_\chi h_\alpha, \tag{8}$$

where α runs over e, μ and τ. Eq. (7) shows that U_ω receives a small correction:

$$U_\omega \to U_\omega' = \left(\mathbf{1} + \frac{HH^\dagger}{M_E^2} \right) U_\omega. \tag{9}$$

It is actually U_ω' that characterizes the contribution of charged leptons to the lepton flavor mixing in this A_4 model.

Now we turn to the neutrino sector. The type-I seesaw mechanism [12] is implemented in the A_4 model under consideration, and thus the overall neutrino mass matrix is a symmetric 6×6 matrix:

$$\mathcal{M}_{\nu\nu^c} = \begin{pmatrix} \mathbf{0} & f_\nu v_u \mathbf{1} \\ f_\nu v_u \mathbf{1} & M_R \end{pmatrix}, \tag{10}$$

where M_R takes the form

$$M_R = \begin{pmatrix} f_{S_b} v_s & 0 & f_{\chi'} v_{\chi'} \\ 0 & f_{S_b} v_s & 0 \\ f_{\chi'} v_{\chi'} & 0 & f_{S_b} v_s \end{pmatrix}. \tag{11}$$

The symmetric neutrino mass matrix in Eq. (10) can be diagonalized via the orthogonal transformation $V_\nu^T \mathcal{M}_{\nu\nu^c} V_\nu$, where the unitary matrix V_ν is given by

$$V_\nu \simeq \begin{pmatrix} \mathbf{1} - \frac{1}{2} \cdot \frac{|f_\nu|^2 v_u^2}{M_R^* M_R^T} & \frac{f_\nu^* v_u}{M_R^*} \\ -\frac{f_\nu v_u}{M_R} & \mathbf{1} - \frac{1}{2} \cdot \frac{|f_\nu|^2 v_u^2}{M_R^T M_R^*} \end{pmatrix} \begin{pmatrix} U_\nu P_\nu & 0 \\ 0 & U_R \end{pmatrix} \tag{12}$$

to a good degree of accuracy. In this expression U_ν has been given in Eq. (2), P_ν denotes a diagonal phase matrix [11], and U_R is a unitary matrix responsible for the diagonalization of M_R. The masses of three light (active) neutrinos turn out to be $m_1 \simeq |m_0(1 + x)|$, $m_2 \simeq |m_0(1 + x)(1 - x)|$ and $m_3 \simeq |m_0(1 - x)|$, where

$$m_0 = \frac{f_\nu^2 v_u^2 f_{S_b} v_s}{f_{S_b}^2 v_s^2 - f_{\chi'}^2 v_{\chi'}^2}, \qquad x = -\frac{f_{\chi'} v_{\chi'}}{f_{S_b} v_s}. \tag{13}$$

Because both m_0 and x are complex, it is possible to adjust their magnitudes and phases such that the resultant values of m_i (for $i = 1, 2, 3$) satisfy current experimental data on the neutrino mass spectrum [11]. Eq. (12) shows that $U_\nu P_\nu$, which signifies the contribution of neutrinos to the lepton flavor mixing, receives a small correction:

$$U_\nu P_\nu \to U_\nu' P_\nu = \left(\mathbf{1} - \frac{1}{2} \cdot \frac{|f_\nu|^2 v_u^2}{M_R^* M_R^T} \right) U_\nu P_\nu. \tag{14}$$

In other words, U'_ν is not exactly unitary and its departure from U_ν is in general an unavoidable consequence in the type-I seesaw mechanism [13].

3. Non-unitary corrections to V_0

With the help of the results obtained in Eqs. (9) and (14), we are able to calculate the MNSP matrix $V = U'^T_\omega (U'_\nu P_\nu)^*$ and demonstrate its non-unitary deviation from the tri-bimaximal mixing pattern V_0. We find

$$\begin{aligned} V &= U^T_\omega \left(\mathbf{1} + \frac{H^* H^T}{M_E^2}\right)\left(\mathbf{1} - \frac{1}{2}\cdot\frac{|f_\nu|^2 v_u^2}{M_R M_R^\dagger}\right) U^*_\nu P^*_\nu \\ &\simeq V_0 P^*_\nu + \frac{1}{f_\ell^2 v_d^2}\begin{pmatrix} m_e^2 & 0 & 0 \\ 0 & m_\mu^2 & 0 \\ 0 & 0 & m_\tau^2\end{pmatrix} V_0 P^*_\nu \\ &\quad - \frac{1}{2}\cdot\frac{1}{|f_\nu|^2 v_u^2} V_0 \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2\end{pmatrix} P^*_\nu \\ &\simeq Q_l\left[\mathbf{1} + \frac{1}{f_\ell^2 v_d^2}\begin{pmatrix} m_e^2 & 0 & 0 \\ 0 & m_\mu^2 & 0 \\ 0 & 0 & m_\tau^2\end{pmatrix} \right. \\ &\quad - \frac{1}{12}\cdot\frac{1}{|f_\nu|^2 v_u^2} \\ &\quad \left. \times \begin{pmatrix} 2(2m_1^2+m_2^2) & 2(m_2^2-m_1^2) & 2(m_1^2-m_2^2) \\ 2(m_2^2-m_1^2) & m_1^2+2m_2^2+3m_3^2 & 3m_3^2-m_1^2-2m_2^2 \\ 2(m_1^2-m_2^2) & 3m_3^2-m_1^2-2m_2^2 & m_1^2+2m_2^2+3m_3^2 \end{pmatrix}\right] V'_0 P^*_\nu, \end{aligned} \tag{15}$$

where

$$V'_0 = Q_l^* V_0 = \frac{1}{\sqrt{6}}\begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3}\end{pmatrix} Q_\nu, \tag{16}$$

and Q_l and Q_ν have been given below Eq. (2). In obtaining Eq. (15) we have omitted the higher-order and much smaller corrections. Because of $v_u = v\sin\beta$ and $v_d = v\cos\beta$ in the supersymmetric A_4 model under consideration, $v_d \ll v_u$ might hold for a very large value of $\tan\beta$. Depending on the magnitudes of f_ℓ^2 and $|f_\nu|^2$, the term proportional to $1/(f_\ell^2 v_d^2)$ or $1/(|f_\nu|^2 v_u^2)$ in Eq. (15) might not be negligibly small. These two terms, which are inherent in the model itself, measure the non-unitary contribution to V or the departure of V from $V'_0 P^*_\nu$. This observation makes sense since it indicates that the exact tri-bimaximal neutrino mixing pattern V_0 is not an exact consequence of a class of A_4 flavor models.

One may parametrize the analytical result obtained in Eq. (15) as follows:

$$V = Q_l(\mathbf{1} - \eta)V'_0 P^*_\nu = V_0 P^*_\nu - Q_l \eta V'_0 P^*_\nu, \tag{17}$$

where the Hermitian matrix η signifies the non-unitary deviation of V from $V_0 P^*_\nu$. Note that the diagonal phase matrix Q_l in V can always be rotated away through a redefinition of the phases of three charged leptons, and the diagonal phase matrices Q_ν and P^*_ν in V only provide us with the Majorana phases which have nothing to do with leptonic CP violation in neutrino oscillations. Note also that η itself is real in this A_4 model, as one can easily see from Eq. (15), and thus the unitarity violation of V does not give rise to any new CP-violating phases. Moreover, it is impossible to obtain nonzero V_{e3} or θ_{13} from this typical A_4 model, simply because $\eta_{e\mu} = -\eta_{e\tau}$ holds. Such a disappointing observation implies that the residual flavor symmetry remains powerful to keep V_{e3} or θ_{13} vanishing and forbid CP violation, even though the MNSP matrix V is not exactly unitary.

Current experimental data allow us to constrain the matrix elements of η and then constrain the model parameters to some extent. A recent analysis yields [14]

$$|\eta| < \begin{pmatrix} 2.0\times10^{-3} & 6.0\times10^{-5} & 1.6\times10^{-3} \\ 6.0\times10^{-5} & 8.0\times10^{-4} & 1.1\times10^{-3} \\ 1.6\times10^{-3} & 1.1\times10^{-3} & 2.7\times10^{-3}\end{pmatrix}. \tag{18}$$

In view of Eqs. (15) and (16), we immediately obtain

$$\begin{aligned} \eta_{e\mu} &= -\eta_{e\tau} = \frac{\Delta m_{21}^2}{6|f_\nu|^2 v_u^2} = \frac{\Delta m_{21}^2}{6|f_\nu|^2 v^2\sin^2\beta}, \\ \eta_{\mu\tau} &= \frac{\Delta m_{31}^2 + 2\Delta m_{32}^2}{12|f_\nu|^2 v_u^2} \simeq \frac{\Delta m_{31}^2}{4|f_\nu|^2 v^2 \sin^2\beta}, \end{aligned} \tag{19}$$

where $\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \simeq 7.6\times10^{-5}$ eV^2 and $\Delta m_{31}^2 \equiv m_3^2 - m_1^2 \simeq m_3^2 - m_2^2 \equiv \Delta m_{32}^2 \simeq \pm 2.4\times10^{-3}$ eV^2 [2]. Eq. (19) leads us to a simple but instructive relation for three off-diagonal matrix elements of η:

$$\frac{\eta_{e\mu}}{\eta_{\mu\tau}} = -\frac{\eta_{e\tau}}{\eta_{\mu\tau}} \simeq \frac{2}{3}\cdot\frac{\Delta m_{21}^2}{\Delta m_{31}^2}. \tag{20}$$

Therefore, $|\eta_{e\mu}|/|\eta_{\mu\tau}| = |\eta_{e\tau}|/|\eta_{\mu\tau}| \simeq 2.1\times10^{-2}$. Comparing this prediction with Eq. (18), one may self-consistently get $|\eta_{e\mu}| = |\eta_{e\tau}| < 2.3\times10^{-5}$ by taking $|\eta_{\mu\tau}| < 1.1\times10^{-3}$. So it is more appropriate to use the upper bound of $|\eta_{\mu\tau}|$ to constrain the lower bound of $|f_\nu|$ by means of Eq. (19). We arrive at

$$|f_\nu| = \frac{1}{2v\sin\beta}\cdot\frac{\sqrt{|\Delta m_{31}^2|}}{\sqrt{|\eta_{\mu\tau}|}} > \frac{4.2}{\sin\beta}\times10^{-12}. \tag{21}$$

This result, which depends on the value of $\tan\beta$ in the supersymmetric A_4 model, implies that the Yukawa coupling of neutrinos should not be too small in order to preserve the unitarity of V at an experimentally-allowed level. It clearly indicates that an arbitrary choice of f_ν in the neglect of small unitarity violation of V is inappropriate for model building, because the correlation between f_ν and the deviation of V from the tri-bimaximal mixing pattern is an intrinsic property of a class of A_4 models.

The diagonal matrix elements of η consist of the contributions from both the charged-lepton sector and the neutrino sector, as shown in Eq. (15). Their competition depends on the sizes of f_ℓ, f_ν and $\tan\beta$. For simplicity, here we assume that the charged-lepton contribution to $\eta_{\alpha\alpha}$ (for $\alpha = e, \mu, \tau$) is dominant. Then it is straightforward to obtain

$$\eta_{\alpha\alpha} \simeq -\frac{m_\alpha^2}{f_\ell^2 v_d^2} = -\frac{m_\alpha^2}{f_\ell^2 v^2\cos^2\beta}. \tag{22}$$

As a result,

$$\eta_{ee} : \eta_{\mu\mu} : \eta_{\tau\tau} \simeq m_e^2 : m_\mu^2 : m_\tau^2 \simeq 1 : 44\,566 : 12\,880\,040, \tag{23}$$

where we have input the central values of three charged-lepton masses at the electroweak scale [15]. Comparing this prediction with Eq. (18), one may self-consistently arrive at $|\eta_{ee}| < 2.1\times10^{-10}$ and $|\eta_{\mu\mu}| < 9.3\times10^{-6}$ by taking $|\eta_{\tau\tau}| < 2.7\times10^{-3}$. It is therefore more appropriate to use the upper bound of $|\eta_{\tau\tau}|$ to constrain the lower bound of $|f_\ell|$ with the help of Eq. (22). We find

$$|f_\ell| \simeq \frac{m_\tau}{v\cos\beta\sqrt{|\eta_{\tau\tau}|}} > \frac{0.19}{\cos\beta}, \quad (24)$$

where $m_\tau \simeq 1746.24$ MeV has been input at the electroweak scale [15]. This result, which also depends on the value of $\tan\beta$ in the supersymmetric A_4 model, shows that the Yukawa coupling of charged leptons should be relatively large in order to preserve the unitarity of V as constrained by current measurements. We stress that an arbitrary choice of either f_ℓ or f_ν in the neglect of small unitarity violation of V might be problematic for model building, simply because they receive constraints both from the model itself and from the experimental data. In this sense one must be cautious to claim that an A_4 flavor model can predict the tri-bimaximal neutrino mixing pattern whose matrix elements are constant and thus have nothing to do with the model parameters [16]. In fact, the slight (non-unitary) deviation of V from the tri-bimaximal mixing pattern is likely to impose a strong restriction on some model parameters like f_ℓ, f_ν and $\tan\beta$.

4. Summary

We have examined a class of A_4 flavor models to see whether the tri-bimaximal neutrino mixing pattern V_0 is an exact consequence of such models. We find that small corrections to V_0 are actually inherent in the A_4 models and may arise from both the charged-lepton and neutrino sectors. We have demonstrated that such corrections may lead the MNSP matrix V to a non-unitary deviation from V_0, but they cannot result in a nonzero V_{e3} (or θ_{13}) or any new CP-violating phases. In particular, the slight unitarity violation of V is sensitive to several model parameters, including the Yukawa couplings of charged leptons and neutrinos. We have shown that current experimental constraints on the unitarity of V allow us to constrain the model parameters to some extent.

We stress that the departure of V from V_0 explored in this work is an intrinsic property of a class of flavor models with the non-Abelian A_4 symmetry. Different departures may result either from the vacuum-expectation-value misalignments in a certain A_4 model or from some purely phenomenological perturbations [17]. The non-unitary deviation of V from V_0 is in some sense more interesting because it might give rise to new CP-violating effects in a variety of long-baseline neutrino oscillation experiments [18]. Since a lot of attention has been paid to how to derive the tri-bimaximal neutrino mixing pattern V_0, the points revealed in our Letter should be taken into account when one attempts to build specific flavor models with discrete family symmetries.

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