CP violation in $\mathrm{B} \to \phi \mathrm{K_S}$ decay in R-parity violating supersymmetry*

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Abstract In the framework of R-parity violating supersymmetry, we investigate the time dependent CP asymmetry $S_{\phi \mathrm{K_S}}$ anomaly of $\mathrm{B} \to \phi \mathrm{K_S}$ decay. When the values of the weak phase ϕ in the R-parity violating coupling fall into certain parameter spaces ($246^\circ < \phi < 263^\circ$) we find that this anomaly can be easily explained; at the same time, the branching ratio of $\mathrm{B} \to \phi \mathrm{K_S}$ decay can also be in agreement with experimental measurements.

Key words RPV SUSY, CP asymmetry, QCD factorization

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1 Introduction

The study of exclusive non-leptonic weak decays of B meson systems provides not only a good opportunity to test the Standard Model (SM) but also a powerful means of probing different new physics (NP) scenarios beyond the SM. In this respect, the B factories at Cornell, SLAC, and KEK are doing a commendable job by churning out a huge amount of data on various B decay modes. The measurements of the time dependent CP asymmetry $S_{\mathrm{J}/\psi \mathrm{K_S}}$ of $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K_S}$ decay have established the presence of CP violation in neutral B meson decays. The world average of the time dependent CP asymmetry of $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K_S}$ and the measured value[1]

$$S_{\mathrm{J}/\psi \mathrm{K_S}} = \sin(2\beta)_{\mathrm{J}/\psi \mathrm{K_S}} = 0.734 \pm 0.054 \tag{1}$$

is consistent with the SM expectation[2]. However, recent measurements of the time dependent CP asymmetry $S_{\phi \mathrm{K_S}}$ of $\mathrm{B} \to \phi \mathrm{K_S}$ decay disagree with the above value. Recently, Belle and BaBar have reported the newest data about the CP asymmetry of $\mathrm{B} \to \phi \mathrm{K_S}$ decay

$$S_{\phi \mathrm{K_S}} = 0.50 \pm 0.23,\ A_{\phi \mathrm{K_S}} = 0.11 \pm 0.16 \text{ Belle}^{[3]}, \tag{2}$$

$$S_{\phi \mathrm{K_S}} = 0.10 \pm 0.29, A_{\phi \mathrm{K_S}} = -0.28 \pm 0.20 \text{ BaBar}^{[4]}. \tag{3}$$

Combining the data from the two experiments, we can obtain

$$S_{\phi \mathrm{K_S}} = 0.35 \pm 0.19, \quad A_{\phi \mathrm{K_S}} = -0.04 \pm 0.13\,. \tag{4}$$

Within the SM, because the difference between the asymmetries of $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K_S}$ and $\mathrm{B} \to \phi \mathrm{K_S}$ decay is expected to be[2]

$$S_{\phi \mathrm{K_S}} = S_{\mathrm{J}/\psi \mathrm{K_S}} + \mathcal{O}(\lambda^2) \tag{5}$$

where $\lambda \approx 0.2$, these results still indicate 2σ deviation from the SM prediction and may reveal new physics effects.

A large amount of theoretical effort has gone into examining the possible NP contributions[5, 6]. In particular, in Ref. [5], A. Datta has discussed the time dependent CP asymmetry $S_{\phi \mathrm{K_S}}$ anomaly of $\mathrm{B} \to \phi \mathrm{K_S}$ decay in the presence of R-parity violating supersymmetry (RPV SUSY). However, the authors obtain quite loose constraints on the weak phase ϕ in the R-parity violation, furthermore the data of the time dependent CP asymmetry $S_{\phi \mathrm{K_S}}$ they used are obviously different from the current ones. In this paper, according to the newest data and using a QCD factorization approach for $\mathrm{B} \to \mathrm{PV}$[7], we provide a solution for the time dependent CP asymmetry $S_{\phi \mathrm{K_S}}$

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anomaly in the framework of RPV SUSY and obtain more stringent constraints on the weak phase ϕ in the R-parity violation.

The paper is organized as follows. In the next section we give a very brief introduction to RPV SUSY. We discuss the CP asymmetry of $\mathrm{B}\to\phi\mathrm{K_S}$ decay in Section 3. Our conclusions are in Section 4.

2 RPV SUSY

R-parity symmetry was first introduced by Farrar and Fayet[8], and was assumed to forbid gauge invariant lepton and baryon number violating operators[9]. The R-parity of a particle field is given by

$$R=(-1)^{3B+L+2S} \tag{6}$$

where B denotes the baryon number, L the lepton number, and S the spin of the SUSY particle, respectively. Apparently, lepton and/or baryon number violation could lead to RPV.

The explicit RPV would introduce renormalizable bilinear higgsino-lepton field mixings and trilinear Yukawa couplings between the ordinary quark and lepton matter particles and the squark and slepton superpartner particles[10]

$$\begin{aligned}\mathcal{W}_{\mathrm{RPV}} = &\sum_{\mathrm{i}}\mu_{\mathrm{i}}\hat{L}_{\mathrm{i}}\hat{H}_{\mathrm{u}}+\sum_{\mathrm{i,j,k}}\left(\frac{1}{2}\lambda_{[\mathrm{ij}]\mathrm{k}}\hat{L}_{\mathrm{i}}\hat{L}_{\mathrm{j}}\hat{E}^{\mathrm{c}}_{\mathrm{k}}+\right.\\ &\left.\lambda'_{\mathrm{ijk}}\hat{L}_{\mathrm{i}}\hat{Q}_{\mathrm{j}}\hat{D}^{\mathrm{c}}_{\mathrm{k}}+\frac{1}{2}\lambda''_{\mathrm{i[jk]}}\hat{U}^{\mathrm{c}}_{\mathrm{i}}\hat{D}^{\mathrm{c}}_{\mathrm{j}}\hat{D}^{\mathrm{c}}_{\mathrm{k}}\right),\end{aligned} \tag{7}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{RPV}} = &\sum_{\mathrm{i}}\mu_{\mathrm{i}}(\bar{\nu}_{\mathrm{iR}}\tilde{H}^{0\mathrm{c}}_{\mathrm{uL}}-\bar{e}_{\mathrm{iR}}\tilde{H}^{+\mathrm{c}}_{\mathrm{uL}})+\\ &\sum_{\mathrm{i,j,k}}\left\{\frac{1}{2}\lambda_{\mathrm{ijk}}\left[\tilde{\nu}_{\mathrm{iL}}\bar{e}_{\mathrm{kR}}e_{\mathrm{jL}}+\tilde{e}_{\mathrm{jL}}\bar{e}_{\mathrm{kR}}\nu_{\mathrm{iL}}+\right.\right.\\ &\left.\tilde{e}^{*}_{\mathrm{kR}}\bar{\nu}^{\mathrm{c}}_{\mathrm{iR}}e_{\mathrm{jL}}-(\mathrm{i}\to\mathrm{j})\right]+\\ &\lambda'_{\mathrm{ijk}}\left[\tilde{\nu}_{\mathrm{iL}}\bar{d}_{\mathrm{kR}}d_{\mathrm{jL}}+\tilde{d}_{\mathrm{jL}}\bar{d}_{\mathrm{kR}}\nu_{\mathrm{iL}}+\tilde{d}^{*}_{\mathrm{kR}}\bar{\nu}^{\mathrm{c}}_{\mathrm{iR}}d_{\mathrm{jL}}-\right.\\ &\left.\tilde{e}_{\mathrm{iL}}\bar{d}_{\mathrm{kR}}u_{\mathrm{jL}}-\tilde{u}_{\mathrm{jL}}\bar{d}_{\mathrm{kR}}e_{\mathrm{iL}}-\tilde{d}^{*}_{\mathrm{kR}}\bar{e}^{\mathrm{c}}_{\mathrm{iR}}u_{\mathrm{jL}}\right]+\\ &\frac{1}{2}\lambda''_{\mathrm{ijk}}\epsilon_{\alpha\beta\gamma}\left[\tilde{u}^{*}_{\mathrm{i}\alpha\mathrm{R}}\bar{d}_{\mathrm{j}\beta\mathrm{R}}d^{\mathrm{c}}_{\mathrm{k}\gamma\mathrm{L}}+\tilde{d}^{*}_{\mathrm{j}\beta\mathrm{R}}\bar{u}_{\mathrm{i}\alpha\mathrm{R}}d^{\mathrm{c}}_{\mathrm{k}\gamma\mathrm{L}}+\right.\\ &\left.\left.\tilde{d}^{*}_{\mathrm{k}\gamma\mathrm{R}}\bar{u}_{\mathrm{i}\alpha\mathrm{R}}d^{\mathrm{c}}_{\mathrm{j}\beta\mathrm{L}}\right]\right\},\end{aligned} \tag{8}$$

where $\hat{L}$ and $\hat{Q}$ are the $SU(2)$-doublet lepton and quark superfields and $\hat{E}^{\mathrm{c}}$, $\hat{U}^{\mathrm{c}}$ and $\hat{D}^{\mathrm{c}}$ are the singlet superfields, while i, j, k are generation indices and c denotes a charge conjugate field.

The λ and λ' couplings in Eq. (7) break lepton number and the λ'' couplings break baryon number conservations. There are 27 λ'-type couplings, 9 λ and 9 λ'' couplings. $\lambda_{[\mathrm{ij}]\mathrm{k}}$ is antisymmetric with respect to the first two indices, and $\lambda''_{\mathrm{i[jk]}}$ is antisymmetric with j and k. The non-observation of proton decay imposes very stringent conditions on the simultaneous presence of both the baryon-number and the lepton-number violating terms in the Lagrangian[11]. It is therefore customary to assume the existence of either L-violating couplings or B-violating couplings, but not both.

3 $\mathrm{B}\to\phi\mathrm{K_S}$ decay

In the SM, the effective Hamiltonian responsible for $\bar{\mathrm{b}}\to\bar{\mathrm{s}}$ transitions is found to be[12]

$$\begin{aligned}\mathcal{H}_{\mathrm{eff}}= &\frac{G_{\mathrm{F}}}{\sqrt{2}}\left[V_{\mathrm{ub}}V^{*}_{\mathrm{us}}(C_1Q^{\mathrm{u}}_1+C_2Q^{\mathrm{u}}_2)+\right.\\ &V_{\mathrm{cb}}V^{*}_{\mathrm{cs}}(C_1Q^{\mathrm{c}}_1+C_2Q^{\mathrm{c}}_2)-\\ &\left.V_{\mathrm{tb}}V^{*}_{\mathrm{ts}}\left(\sum_{i=3}^{10}C_iQ_i+C_{7\gamma}Q_{7\gamma}+C_{8\mathrm{g}}Q_{8\mathrm{g}}\right)\right]+\mathrm{h.c.},\end{aligned} \tag{9}$$

where $V_{\mathrm{qb}}V^{*}_{\mathrm{qs}}$ ($\mathrm{q}=\mathrm{u,c,t}$) are CKM factors, C_i are the effective Wilson coefficients and Q_i the relevant four-quark operations.

According to QCD factorization[7], when the final-state hadrons emitted from B-meson decay are both light ones, the matrix element of each operator in the effective Hamiltonian can be written as

$$\begin{aligned}\langle M_1M_2|Q_i|B\rangle = &\sum_j F_j^{B\to M_1}\int_0^1\mathrm{d}xT^{\mathrm{I}}_{ij}(x)\Phi_{M_2}(x)+\\ &(M_1\leftrightarrow M_2)+\int_0^1\mathrm{d}\xi\int_0^1\mathrm{d}x\int_0^1\mathrm{d}yT^{\mathrm{II}}_i(\xi,x,y)\times\\ &\Phi_B(\xi)\Phi_{M_1}(x)\Phi_{M_2}(y),\end{aligned} \tag{10}$$

where $F_j^{B\to M_1}$ is the transition form factor, the kernels T^{I}_{ij} and T^{II}_i denote the short-distance contributions and can be calculated perturbatively, and $\Phi_X(X=B,M_{1,2})$ are universal nonperturbative light cone distribution amplitudes of the corresponding mesons. Since the weak annihilation contributions are suppressed by $1/m_{\mathrm{b}}$ in the heavy quark limit, they are not included in Eq. (10).

With the effective Hamiltonian Eq. (9) and the QCD factorization formula Eq. (10), we can write out the decay amplitude for a general two-body charmless

$B\to M_1M_2$ decay as

$$\mathcal{A}(B\to M_1M_2)=\frac{G_F}{\sqrt{2}}\sum_{p=u,c}\sum_i V_{pb}V_{ps}^*\alpha_i^p\times(\mu)\langle M_1M_2|Q_i|B\rangle_F, \quad (11)$$

where $\langle M_1M_2|Q_i|B\rangle_F$ is the factorized matrix element, the general form of the effective coefficients $\alpha_i^p(M_1M_2)$ $(i=1,\cdots,10)$ at next-leading order is given as[7]

$$\alpha_i^p(M_1M_2)=\left(C_i+\frac{C_{i\pm1}}{N_c}\right)N_i(M_2)+\frac{C_{i\pm1}}{N_c}\frac{C_F\alpha_s}{4\pi}\times\left[V_i(M_2)+\frac{4\pi^2}{N_c}H_i(M_1M_2)\right]+P_i^p(M_2), \quad (12)$$

where the upper (lower) signs "$\pm$" apply when i is odd (even), the quantities $V_i(M_2)$ account for one-loop vertex corrections, $H_i(M_1M_2)$ for hard spectator interactions, and $P_i^p(M_2)$ for penguin contractions. The explicit expressions for these functions an be found in Ref. [7].

We also consider weak annihilation contributions, which can be expressed as

$$\mathcal{A}^{\text{ann}}(B\to M_1M_2)\propto\frac{G_F}{\sqrt{2}}\sum_{p=u,c}\sum_i\lambda'_p f_B f_{M_1}f_{M_2}b_i(M_1M_2), \quad (13)$$

where f_B and f_M are the decay constants of the initial B and the final-state mesons, respectively, and the parameters $b_i(M_1M_2)$ are defined as

$$\begin{aligned}
b_1(M_1M_2)&=\frac{G_F}{N_c^2}C_1A_1^i, &\quad b_3^p(M_1M_2)&=\frac{G_F}{N_c^2}\left[C_3A_1^i+C_5(A_3^i+A_3^f)+N_cC_6A_3^f\right],\\
b_2(M_1M_2)&=\frac{G_F}{N_c^2}C_2A_1^i, &\quad b_{3,EW}^p(M_1M_2)&=\frac{G_F}{N_c^2}\left[C_9A_1^i+C_7(A_3^i+A_3^f)+N_cC_8A_3^f\right],\\
b_4^p(M_1M_2)&=\frac{G_F}{N_c^2}\left[C_4A_1^i+C_6A_2^i\right], &\quad b_{4,EW}^p(M_1M_2)&=\frac{G_F}{N_c^2}\left[C_{10}A_1^i+C_8A_2^i\right],
\end{aligned} \quad (14)$$

where the explicit expressions for the basic building blocks $A_k^{i,f}$ can be found in Ref. [7].

In the SM, the amplitude of $B_d\to\phi K_S$ decay can be written as

$$\mathcal{A}_{\phi K_S}^{SM}=\frac{G_F}{\sqrt{2}}A_{K_S\phi}\sum_{p=u,c}V_{pb}V_{ps}^*\left[\alpha_3^p+\alpha_4^p-\frac{1}{2}\alpha_{3,EW}^p-\frac{1}{2}\alpha_{4,EW}^p+\beta_3^p-\frac{1}{2}\beta_{3,EW}^p\right], \quad (15)$$

where

$$A_{K_S\phi}=2f_\phi m_\phi F_{BK}(m_\phi^2)\varepsilon^*\cdot p_B\,. \quad (16)$$

The branching ratio of $B_d\to\phi K_S$ decay in the B meson rest frame can be written as

$$B_r=\frac{\tau_B p_c}{8\pi M_B^2}\left|\mathcal{A}(B_d\to\phi K_S)\right|^2 \quad (17)$$

where

$$p_c=\frac{\sqrt{[M_B^2-(M_{K_S}+M_\phi)^2][M_B^2-(M_{K_S}-M_\phi)^2]}}{2M_B}\,, \quad (18)$$

denotes the center of mass momentum of the meson ϕ or K_S in the B_d rest frame.

For $B_d\to\phi K_S$ decay, the time-dependent CP asymmetry is

$$a_{\phi K_S}=\frac{\Gamma(\bar{B}^0(t)\to\phi K_S)-\Gamma(B^0(t)\to\phi K_S)}{\Gamma(\bar{B}^0(t)\to\phi K_S)+\Gamma(B^0(t)\to\phi K_S)}=A_{\phi K_S}\cos(\Delta M_{B_d}t)+S_{\phi K_S}\sin(\Delta M_{B_d}t)\,, \quad (19)$$

where the direct and indirect CP asymmetry parameters are given respectively by

$$A_{\phi K_S}=\frac{|\lambda_{\phi K_S}|^2-1}{|\lambda_{\phi K_S}|^2+1},\quad S_{\phi K_S}=\frac{2\text{Im}[\lambda_{\phi K_S}]}{|\lambda_{\phi K_S}|^2+1}. \quad (20)$$

The parameter $\lambda_{\phi K_S}$ is defined as

$$\lambda_{\phi K_S}\equiv\eta_{\phi K_S}\left(\frac{q}{p}\right)_B\left(\frac{p}{q}\right)_K\frac{\bar{A}(\phi\bar{K}^0)}{A(\phi K^0)}, \quad (21)$$

where $\eta_{\phi K_S}=-1$ is the CP eigenvalue of the ϕK_S state, and

$$\left(\frac{q}{p}\right)_B=\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*},\qquad\left(\frac{p}{q}\right)_K=\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}. \quad (22)$$

According to Eq. (8), the terms proportional to λ are not relevant to our present discussion and will not be considered further. The antisymmetry of the B-violating couplings, $\lambda''_{i[jk]}$ in the last two indices, implies that there are no operators that can generate the $\bar{b}\to\bar{s}s\bar{s}$ transition, and hence can not contribute to $B_d\to\phi K_S$, at least at the tree level.

For the $\bar{b}\to\bar{s}s\bar{s}$ transition, the revelant Lagrangian is[5]

$$\mathcal{L}_{\text{eff}}=\frac{\lambda'_{i22}\lambda'^*_{i32}}{m_{\tilde{\nu}_i}^2}\bar{s}\gamma_L s\bar{s}\gamma_R b+\frac{\lambda'^*_{i22}\lambda'_{i23}}{m_{\tilde{\nu}_i}^2}\bar{s}\gamma_R s\bar{s}\gamma_L b\,, \quad (23)$$

where $\gamma_{LR}=\dfrac{(1\mp\gamma_5)}{2}$.

The RPV contribution can be written as

$$\mathcal{A}^{\rm RPV}_{\phi K_S} = (X_1+X_2)A_{K_S\phi},$$
$$X_1 = -\frac{\lambda'_{i22}\lambda'^*_{i32}}{24m^2_{\tilde{\nu}_i}}, \quad (24)$$
$$X_2 = -\frac{\lambda'^*_{i22}\lambda'_{i23}}{24m^2_{\tilde{\nu}_i}},$$

and we write

$$X_1+X_2=\frac{X}{12M^2}e^{i\phi}, \quad (25)$$

where ϕ is the weak phase in R-parity violating couplings and M is some mass scale with $M\sim m_{\tilde{\nu}_i}$ for the RPV contribution. According to Ref. [13], we take $|X|\sim 1.8\times10^{-3}$ for $M=100$ GeV.

We obtain the total decay amplitude

$$\mathcal{A}=\mathcal{A}^{\rm SM}_{\phi K_S}+\mathcal{A}^{\rm RPV}_{\phi K_S}. \quad (26)$$

Obviously, the total decay amplitude is only dependent on the parameter ϕ. To obtain the allowed parameter space, we allow the measured value of $Br(B_d\to\phi K_S)$ to vary by 2σ from its central value; this 2σ band contains both experimental and theoretical errors, and the main source of theoretical error is the form factor F_{BK}. We plot the branching ratio $Br^{\rm SM+RPV}(B_d\to\phi K_S)$ versus the weak phase ϕ in Fig. 1. We obtain

$$128^\circ<\phi<145^\circ, \quad 246^\circ<\phi<263^\circ. \quad (27)$$

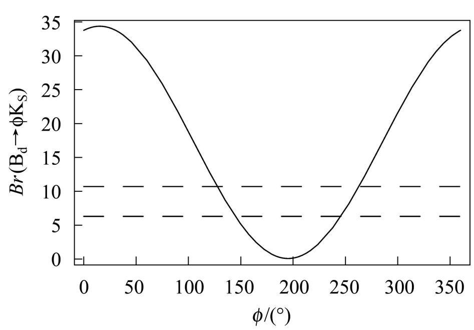

Fig. 1. The branching ratio $Br^{\rm SM+RPV}$ ($B_d\to\phi K_S$) in units of 10^{-6} versus the weak phase ϕ. The horizontal dashed lines are the current world average value $Br=(8.3^{+1.2}_{-1.0})\times10^{-6}$ within 2σ[14]. The solid curve is the branching ratio of $B_d\to\phi K_S$ decay.

If we take the value of the parameter ϕ from these regions, the branching ratio of $B_d\to\phi K_S$ decay is consistent with the current experimental data.

Meanwhile, we also allow the measured value of $S_{\phi K_S}$ to vary by 2σ from its central value and plot the time dependent CP asymmetry $S_{\phi K_S}$ versus the weak phase ϕ in Fig. 2. We obtain

$$0^\circ<\phi<50^\circ, \quad 166^\circ<\phi<268^\circ. \quad (28)$$

Within these parameter spaces, the time dependent CP asymmetry $S_{\phi K_S}$ matches up to the current experimental data.

Simultaneously considering the constraints on the weak phase ϕ from the branching ratio and time dependent CP asymmetry $S_{\phi K_S}$ of $B_d\to\phi K_S$ decay, we obtain

$$246^\circ<\phi<263^\circ. \quad (29)$$

Within this parameter space, the time dependent CP asymmetry $S_{\phi K_S}$ anomaly can be explained; at the same time, the branching ratio of $B_d\to\phi K_S$ decay can also be in agreement with the experimental measurements.

We also examine the direct CP asymmetry $A_{\phi K_S}$ in order to feel for the effects of NP on CP violation. According to the obtained constraints on the weak phase ϕ, we obtain

$$-0.39<A_{\phi K_S}<-0.29, \quad (30)$$

which is zero in the SM. At present, there are large theoretical uncertainties in calculating strong phases.

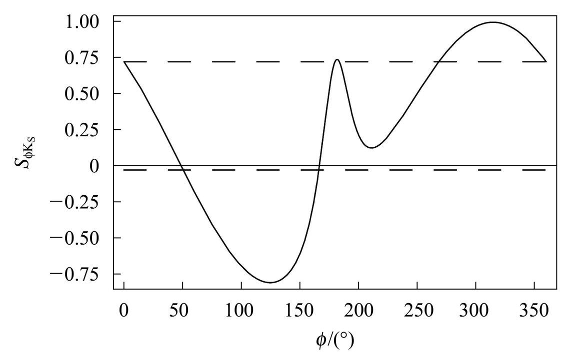

Fig. 2. The time dependent CP asymmetry $S_{\phi K_S}$ versus ϕ. The current experiment ranges of $S_{\phi K_S}$ at the 2σ level are shown by the horizontal dashed lines. The solid curve is $S_{\phi K_S}$.

4 Conclusions

The time dependent CP asymmetry $S_{\phi K_S}$ has long been inconsistent with SM expectations; this anomaly represents a challenge for theoretical interpretation. We have employed the QCD factorization approach to present a study of the RPV SUSY effects on this anomaly. Setting the RPV product couplings, we find that both the time dependent CP asymmetry $S_{\phi K_S}$ and the branching ratio of $B_d\to\phi K_S$ decay are compatible with the experimental results within certain parameter spaces, which are $246^\circ<\phi<263^\circ$. We also show the effects of RPV SUSY on the direct

CP asymmetry $A_{\phi\mathrm{K_S}}$. Our analysis has shown that RPV SUSY plays an important role in resolving the discrepancies between the theoretical predictions in the SM and the experimental data.

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