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The TREK experiment to search for T violation in kaon decays at J-PARC

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The transverse muon polarization (P_T) in $K \to \pi\mu\nu$ ($K_{\mu3}$) decays is a very sensitive probe of T violation. One may look for sources of CP violation beyond the Standard Model. The TREK experiment is a planned J-PARC experiment to search for P_T with a sensitivity of 10^{-4} with an improvement of factor more than 20 from the previous KEK-PS E246 experiment. Currently, detector elements are developed in order to upgrade the E246 detector for higher beam intensity at J-PARC.

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1. Introduction

Violation of time reversal invariance (T) is one of the important issues in particle physics along with CP violation. The transverse muon polarization (P_T) in $K \to \pi\mu\nu$ ($K_{\mu 3}$) decays with T-odd correlation was suggested by Sakurai [1] about 50 years ago to be a clear signature of T violation. Unlike other T-odd channels in e.g. nuclear beta decays, P_T has the advantage that the final state interactions (FSI), which may mimic T violation by inducing a spurious T-odd effect, are very small [2]. This argument applies most particularly to $K^+_{\mu 3}$ decay with only one charged particle in the final state. Hence, dedicated experiments have been carried out in search of non-zero P_T in $K^+_{\mu 3}$ decays [3] over the last two decades. An important feature of a P_T study is the fact that the contribution to P_T from the Standard Model (SM) is nearly zero ($\sim 10^{-7}$). Therefore, in a P_T search we are investigating new physics beyond the SM. T violation has also an important meaning since it is equivalent to CP violation according to the CPT theorem. We can study the sources of CP violation which are necessary to explain the baryon asymmetry in the universe.

The most recent research of P_T has been performed at the KEK proton synchrotron as the E246 experiment. Its result was consistent with no T violation but provided the world best limit of $P_T = -0.0017 \pm 0.0023\ (stat) \pm 0.0011\ (syst)$ [4] and constrained the parameter spaces of several contender models. It was, however, statistics limited, mainly due to insufficient accelerator beam intensity in spite of smaller systematic errors. Now we intend to continue the P_T experiment further at J-PARC where higher accelerator beam intensity will be available and a higher experimental sensitivity is promised, in order to search for new physics beyond SM. We aim for a sensitivity of $\delta P_T \sim 10^{-4}$ [5].

2. Muon Transverse Polarization in $K^+ \to \pi^0\mu^+\nu$ Decay

2.1 $K^+ \to \pi^0\mu^+\nu$ decay

The decay matrix element of the $K_{\mu 3}$ decay based on the V-A theory can be written as [6]

$$M = \frac{G_F}{2}\sin\theta_c \left[f_+(q^2)(p_K^\lambda + p_\pi^\lambda) + f_-(q^2)(p_K^\lambda - p_\pi^\lambda) \right] \cdot \left[\overline{u}_\nu \gamma_\lambda (1-\gamma_5) v_\mu \right] \tag{2.1}$$

with two form factors $f_+(q^2)$ and $f_-(q^2)$ of the momentum transfer squared to the lepton pair, $q^2 = (p_K - p_\pi)^2$. Here, G_F is the Fermi constant, θ_c the Cabibbo angle, p_K, p_π, p_μ and p_ν are the four-momenta of the kaon, pion, muon and anti-neutrino, respectively. Using $p_K = p_\pi + p_\mu + p_\nu$, this amplitude can be rewritten as

$$M = \frac{G_F}{2}\sin\theta_c f_+(q^2) \left[2p_K^\lambda \cdot \overline{u}_\nu \gamma_\lambda (1-\gamma_5) v_\mu + (\xi(q^2) - 1) m_\mu \overline{u}_\nu (1-\gamma_5) v_\mu \right] \tag{2.2}$$

where the parameter $\xi(q^2)$ is defined as $\xi(q^2) = f_-(q^2)/f_+(q^2)$.

2.2 Transverse Polarization

P_T is induced from the complex phase of ξ, the weighted average of $\xi(q^2)$ over q^2, and can be written in terms of Imξ and a kinematical factor as

$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|\vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]}. \tag{2.3}$$

The quantity $\mathrm{Im}\xi$, sensitive to the T-violation, can be thus determined from a P_T measurement. The kinematic factor as a function of the π^0 energy and μ^+ energy has an average value of ~ 0.3 yielding a full detector acceptance relation of $< P_T > \sim 0.3\,\mathrm{Im}\xi$.

It is of interest to establish the connection between the $\mathrm{Im}\xi$ and effective parameters of new physics appearing in the coefficients of generic exotic interactions. To this end, an effective four fermion Lagrangian can be used:

$$\begin{aligned} L = & - \frac{G_F}{\sqrt{2}} \sin\theta_C \bar{s}\gamma_\alpha(1-\gamma_5)u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu \\ & + G_S\bar{s}u\,\bar{\nu}(1+\gamma_5)\mu + G_P\bar{s}\gamma_5 u\,\bar{\nu}(1+\gamma_5)\mu \\ & + G_V\,\bar{s}\gamma_\alpha u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + G_A\bar{s}\gamma_\alpha\gamma_5 u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + \mathrm{h.c.}. \end{aligned} \tag{2.4}$$

Here, G_S and G_P are the scalar and pseudo-scalar coupling constants and G_V and G_A are the exotic vector and axial-vector coupling constants, respectively. $\mathrm{Im}\xi$ is found to be caused only by the interference between the SM term and the scalar term, namely by the complex phase of G_S [7, 8], which can be written as

$$\mathrm{Im}\xi = \frac{(m_K^2 - m_\pi^2)\mathrm{Im}G_S^*}{\sqrt{2}(m_s - m_u)m_\mu G_F \sin\theta_C} \tag{2.5}$$

where m_s and m_u are the masses of the s-quark and u-quark, respectively. Thus, P_T can constrain the exotic scalar interactions. The situation is different in the similar transverse muon polarization P_T in the radiative kaon decay $K^+ \to \mu^+\nu\gamma$, which is caused by pseudo-scalar interactions G_P [8].

2.3 Theoretical Models

The SM contribution comes from only higher order effects. The possible size of its contribution was once suggested qualitatively in [9] to be less than $P_T < 10^{-6}$. An actual value based on the lowest-order vertex radiative corrections was presented in the textbook of Bigi and Sanda [10]. This has been estimated to be less than 10^{-7}. This fact constitutes the main motivation of the physics background for P_T experiment as a search for new physics. Since the effect arising from FSI is known to be of the order of 10^{-5} [2] and it is calculable, an observation of a non-zero P_T implies unambiguously the existence of CP violation mechanisms beyond the SM, namely new physics. Assuming 10^{-6} for the accuracy for the FSI estimation, there is a large window to explore from the current limit of $P_T \sim 10^{-3}$, while several new physics models allow the appearance of P_T in the ranges of $10^{-4} \sim 10^{-3}$ level.

As the minimum and natural extension of the SM with one Higgs doublet, multi-Higgs doublet models have been considered, and a number of papers [11, 12, 13] have applied this model to P_T as one of the promising candidate theories. In the class of models without tree-level flavor changing neutral current, new CP violating phases are introduced in the charged Higgs mass matrix if the number of doublets is more than two. The coupling of quarks and leptons to the Higgs boson is expressed in terms of the Lagrangian

$$L = (2\sqrt{2}G_F)^{\frac{1}{2}} \sum_{i=1}^{2} \{\alpha_i \bar{u_L} V M_D d_R H_i^+ + \beta_i \bar{u_R} M_U V d_L H_i^+ + \gamma_i \bar{\nu_L} M_E e_R H_i^+\} + \mathrm{h.c.}, \tag{2.6}$$

where M_D, M_U, M_E are diagonal mass matrices, V is the CKM matrix, and α_i, β_i and γ_i are the new complex coupling constants associated with the charged Higgs interactions. For the three doublet

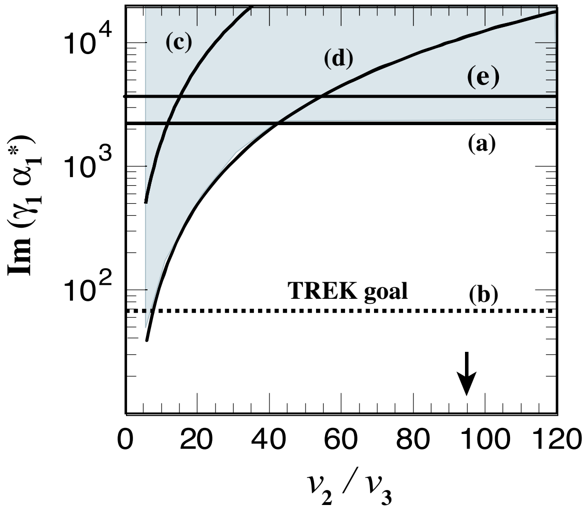

Figure 1: Constraint to the three Higgs doublet model parameters of $|\mathrm{Im}(\gamma_1\alpha_1^*)|$ and v_2/v_3, the ratio of Higgs field vacuum expectation values, with the assumption of $m_{H^+} \cong 2m_Z$. (a) is the P_T limit from the E246 experiment, (b) is P_T expectation in TREK, (c) neutron electric dipole moment (EDM) only with the d-quark contribution, (d) $b \to s\gamma$, (e) $b \to X\tau\nu$. The gray region is the excluded region. The arrow shows the most probable point of v_2/v_3 to be $m_t/m_\tau = 95$.

case a natural flavor conservation can be arranged. The coefficients α_i, β_i and γ_i can have complex phases, and P_T is calculated as

$$\mathrm{Im}\xi = \frac{m_K^2}{m_H^2}\mathrm{Im}(\gamma_1\alpha_1^*), \tag{2.7}$$

where α_1 and γ_1 are the quark and lepton couplings to the lightest charged Higgs boson. The E246 result [5] yielded $|\mathrm{Im}(\gamma_1\alpha_1^*)| < 0.066(m_H/\mathrm{GeV})^2$ as the most stringent limit for this parameter. $(\gamma_1\alpha_1^*)$ is also constrained by the semileptonic decay of the B meson $B \to \tau\nu X$ [14] as the deviation from the SM value, but the constraint on $|\mathrm{Im}(\gamma_1\alpha_1^*)|$ is less stringent than the P_T constraint. The recent observation of $B \to \tau\nu$ [15] constrains the model in a similar manner [16] but less stringent at the moment. Other constraints to this model come from the neutron EDM (d_n), $b \to s\gamma$ and $b \to sl\bar{l}$ complementing the P_T result in a different manner, since these channels limit $\mathrm{Im}(\alpha_1\beta_1^*)$.

Several other models allow P_T at observable level without conflicting with other experimental constraints. A SUSY model with R-parity violation was considered [17] and also a minimal supersymmetric standard model (MSSM) with large squark mixing [18] was investigated.

3. J-PARC TREK Experiment

3.1 Goal of the experiment

Considering the current experimental situation of direct CP violation studies and searches for new physics, it is essential to perform the P_T measurement in $K_{\mu3}^+$ as the TREK[1] experiment [5] at J-PARC, which offers a far superior experimental environment as compared to KEK-PS. The 40

[1]TREK is an acronym of Time Reversal Experiment with Kaons.

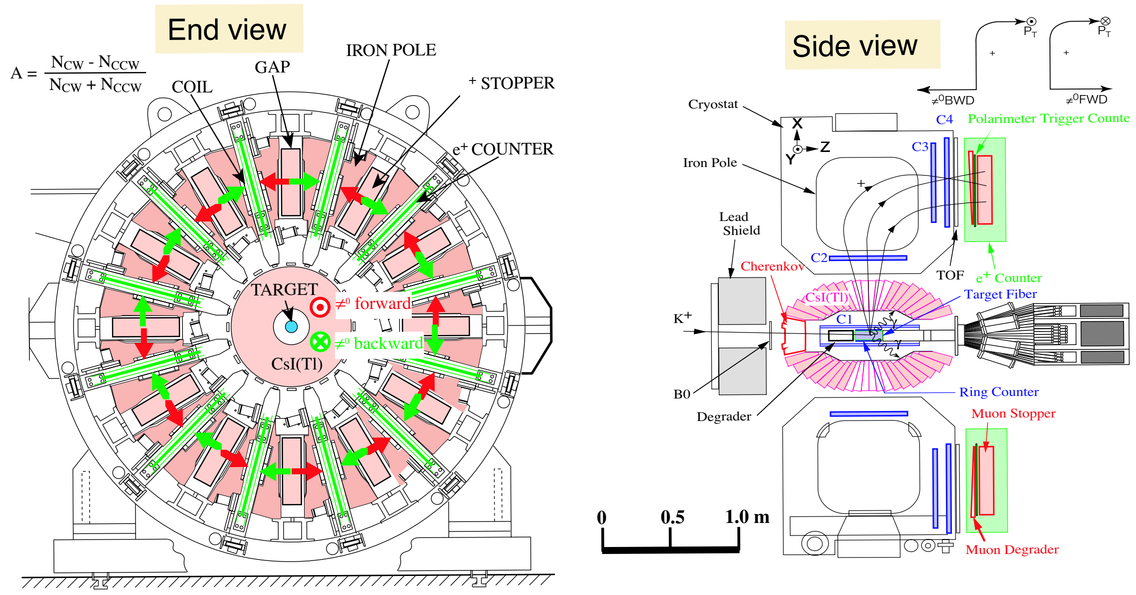

Figure 2: Toroidal magnet setup for the TREK experiment

year history of P_T experiments shows a rather slow improvement in the upper limit. This is due to the nature of this high precision experiment which must be conducted and analyzed very carefully. In TREK we prefer to follow this approach for the J-PARC experiment and to proceed in a steady way to improve the sensitivity.

The E246 result was essentially statistics-limited. This result was foreseen at the start of the experiment. We propose to improve the E246 result by at least a factor 20 ($\delta P_T < 1.2 \times 10^{-4}$), by improving both statistical error (by a factor 20 at least) and systematics uncertainty (by a factor 10 at least). If warranted, further sensitivity improvement towards 10^{-5} will be proposed in the next stage after we have been convinced of the possibility to pursue this experiment to such a high precision region. In order to optimize the performance of the E246 detector [19] based on the Toroidal Spectrometer system, several improvements must be undertaken. We will keep the principal concept of the experiment, namely the application of the muon magnetic field in the azimuthal direction parallel to the P_T component, and the object of the measurement in this experiment is primarily the *cw*-*ccw* positron asymmetry in the azimuthal direction, i.e., we keep the fwd/bwd scheme [4, 5].

3.2 Active polarimeter

The most important feature of the TREK experiment is the adoption of an active polarimeter in contrast to E246 where a passive polarimeter with a separate system of a muon stopper and positron counters was used. The advantage of this passive system was the simplicity of systematics and analysis. However, this was done at the cost of e^+ detection acceptance and polarization analyzing power. We now aim for higher detector acceptance and higher sensitivity by introducing the active polarimeter which should have the following functions and advantages [20].

- Determination of the muon stopping position for each event, which in turn, renders the experiment free from the systematic error associated with the ambiguities in the muon stopping distribution. As the decay positron tracks are measured, the decay vertices will be determined event-by-event. Therefore, data will be in principle background-free.

- Detection of decay positrons in all directions by a polarimeter with a large acceptance with nearly 4π solid angle. In E246 the positron counter solid angle was limited to about 10% on each side. Now the detector acceptance becomes 10 times larger. The ability to measure positron emission angle provides the possibility to use not only the fwd/bwd pion scheme but also the $left/right$ pion scheme.

- Measurement of the positron emission angle, and rough positron energy by means of the number of penetrating stopper plates. The asymmetry changes as the positron energy varies. A weighted analysis brings about a significant increase in the analyzing power resulting in the highest sensitivity.

Needless to say the stopper should have a large muon collection/stopping efficiency and the ability to preserve the polarization. In order 1) to ensure preservation of muon spin polarization, in particular the P_T component, and 2) to decouple stray fields such as the earth field, a magnetic field with a strength of at least 300 G is applied at the stopper with additional dipole magnets.

3.3 Tracking system

In the TREK experiment two sources of systematic errors will dominate. While one source is the misalignment of the detector elements, in particular of the muon polarimeter, the other source will be given by the background contamination of muons from the decay-in-flight of $K_{\pi 2}$ pions ($K_{\pi 2}^{dif}$ events). With the upgrade of the tracking system, the error from this background will be suppressed to meet the requirement of $< 10^{-4}$ for the total systematic error in P_T. The momentum resolution of E246 can be improved by a factor of ten at least 1) by employing a thinner target with finer target segmentation, 2) by replacing the air volume with helium bags, and 3) by increasing the distance between the C3 and C4. For adequate identification and suppression of $K_{\pi 2}^{dif}$ events we need to build a cylindrical tracking chamber C0 with a radius of 10 cm and a spacial resolution of <0.1 mm. In order to increase tracking redundancy we plan to add a new planar tracking element C1 with <0.1 mm resolution to cover each of the 12 gaps at the outer surface of the CsI(Tl) calorimeter. C0 and C1 will be both GEM. By adding these elements, the resulting χ^2 per degree of freedom will be much more effective to distinguish tracks from $K_{\pi 2}^{dif}$ from regular tracks which do not have a kink along their path. In combination with the higher segmentation of the fiber target this will be sufficient to suppress the $K_{\pi 2}^{dif}/K_{\mu 3}$ ratio below 10^{-3} rendering a spurious $P_T < 5 \times 10^{-5}$.

3.4 CsI(Tl) calorimeter

The photon calorimeter is a barrel of 768 CsI(Tl) crystals surrounding the target region. There are 12 so-called muon holes to let the charged particle enter the spectrometer. The solid angle coverage is therefore not 4π sr but about 3π sr including also the losses due to the beam entrance and exit holes. The size of the muon hole was optimized for the $K_{\mu 3}^+$ acceptance to be maximum.

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The barrel was assembled very carefully ensuring a local as well as a global precision of better than 1mm. Considering the limitations in the PIN and preamplifier scheme for high rate operation, we replace this readout system. We adopt avalanche photo-diodes (APD) of reverse bias type. Such APDs with a multiplication factor of about one hundred with reasonably large sensitive areas are commercially available. A several times larger electron yield than the PIN (in E246), allows us to use a current preamplifier with high gain in place of the costly charge preamplifier which would also encounter the rate limitation due to the output voltage dynamic range. A high rate performance test of APD readout has been performed using a positron beam for one crystal module. About 500 kHz signal rate in one module will be tolerable and analyzable using an FADC.

3.5 Beamline

In order to perform the TREK experiment using stopped K^+s, a separate low-momentum K^+ beamline with a good K/π ratio is required. In the Phase-1 experimental hall of J-PARC, however, there will be only one primary proton A-line and only one target station T1. We pursue the possibility of a low-momentum beamline with a beam momentum of 0.8 GeV/c as a branch line of the K1.1 line. The beam optics of this branch has already been designed. The K^+/π^+ ratio of this 0.8 GeV/c branch line is expected to be larger than 2 in spite of a single stage of separation and is sufficiently good for our purposes. The acceptance is, however, determined primarily by the upstream acceptance of K1.1, namely by the distance of the first focusing element from the target, which cannot be shorter. The calculated value of ~ 4.5 msr$(\%\Delta p/p)$ for 0.8 GeV/c operationis smaller by a factor of 10 than the LESB3 line at BNL-AGS of the nearly same length. Although there might be some ambiguity due to the detailed target structure, we can roughly estimate the K^+ intensity to be 2×10^6/s at $I_p = 4\times10^{13}$/s (9μA) and $E_p = 30$ GeV by scaling the known LESB3 intensity at $E_p = 24$ GeV.

4. Sensitivity

For a conservative estimate we assume the sensitivity coefficient for the integral analysis taking only the fwd and bwd regions of the π^0 events. Several comments are presented for the other parameters. First, the average beam intensity at the K0.8 beamline is assumed to be 2×10^6/s as described above. Although it is stated that some beam commissioning period with a low accelerator beam intensity is necessary, our total beam request is 1.4×10^7 s of beam time with this kaon beam intensity. We estimate the sensitivity based on the total number of kaons of 3×10^{13}. Secondly, the fraction of fwd and bwd regions is 30% of the total good $K_{\mu3}$ events including the $left$ and $right$ regions. It is somewhat difficult to estimate the analysis efficiency as it strongly depends on many details. However, at least for now, we can assume that it would be better than what we attained in E246. We use a conservative estimate of 0.67 for the E246 efficiency. The deduction of the statistical error is summarized in Table 1. In the standard fwd/bwd π^0 analysis a statistical error of $\delta P_T = 1.2\times10^{-4}$ will be obtained from a one-year (1.4×10^7 s) run. An analysis including the $left$ and $right$ regions will provide a smaller error of $\delta P_T = 1.0\times10^{-4}$. A more ambitious weighted analysis event-by-event should attain the highest sensitivity of $\delta P_T = 0.8\times10^{-4}$ although the systematic errors have yet to be investigated carefully in this case.

Table 1: Deduction of statistical error

Parameter	Value
Net run time	1.4×10^7s
Proton beam intensity	9μA on T1 target
K^+ beam intensity	2×10^6/s
Total number of good $K_{\mu 3}$	2.4×10^9
Total number of fwd and bwd (N)	7.2×10^8
Sensitivity coefficient	$3.34/\sqrt{N}$
δP_T for fwd and bwd	1.2×10^{-4}
δP_T for all π^0	1.0×10^{-4}
δP_T in weighted analysis	0.8×10^{-4}

5. Summary

In summary, we plan to perform a high precision measurement (TREK experiment) of the transverse polarization of muons, P_T, in the $K^+_{\mu 3}$ decays which constitutes a T-odd observable. This observable is one of the few tests of T-invariance violation corresponding to direct CP violation in neutral meson system. We aim to improve the precision of this measurement at least by a factor of 20 compared to the best result from our own KEK-PS-E246, and to reach a limit of $\delta P_T \sim 10^{-4}$ (Fig.3). The FSI contribution in the SM descriptions is significantly smaller than the sensitivity of this experiment, however several exotic models inspired by multi-Higgs doublet *etc.* allow P_T values within the sensitivity attainable to us. Thus, this experiment is likely to find new sources of CP violation, if any of these models are viable. It will certainly constrain the parameter space of the candidate models. The sensitivity of this experiment is comparable or complementary to that of the proposed new neutron EDM experiments and other rare decay processes, since P_T as a semileptonic process spans the parameter space which is not covered by other channels.

The experiment will be performed using the stopped K^+ beam method as the previous KEK-E246 experiment. This method is suited for a double ratio measurement in terms of π^0 emission direction enabling the efficient suppression of systematic errors, which is essential for the high precision experiment TREK. Although the basic toroidal setup of E246 is used, several upgrades of the detector elements will be done, in order to meet the requirements from higher rate performance, larger acceptance, better background rejection, and more efficient suppression of the systematic errors.

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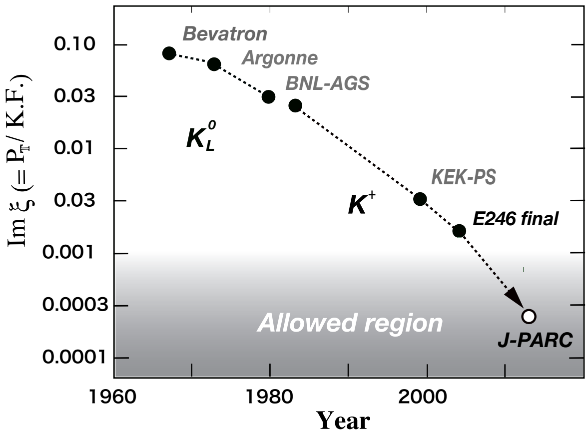

Figure 3: Expected sensitivity (90% C.L. assuming a zero central value) of the TREK experiment.

[5] J-PARC proposal P06; *Measurement of T-violating Muon Polarization in* $K^+ \to \pi^0 \mu^+ \nu$ *Decays* (2006), http://j-parc.jp/NuclPart/Proposal_e.html

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