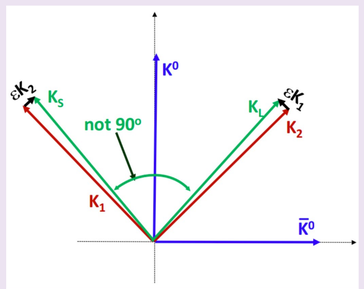
Measurement of *CP* violation of $K^0 - \bar{K}^0$ system at STCF via $J/\psi \to K^-\pi^+K^0$

Jian-Yu Zhang (UCAS)

Abstract: We present a preliminary study of *CP* violation effect of $K^0 - \bar{K}^0$ system in J/ψ decay. The *CP* violation parameters $|\eta_{+-}|$ and its phase ϕ_{+-} can be determined by the difference of the time-dependent decay rates between K^0 and $\bar{K}^0$ produced from $J/\psi \to K^-\pi^+K^0 + c.c.$ processes. We investigate the precisions of the measurements of the *CP* violation effect at the Super Tau-Charm Factory(STCF). The parameters $|\eta_{+-}|$ and its phase ϕ_{+-} can be measured at a relative precision of 1×10^{-3}, which the statistical accuracy will be several times better than that of the existing PDG average values.*

INTRODUCTION

The phenomenon of mixing in neutral kaon system has been of special interest for a long time. Neutral kaons have definite quark components and strangeness S when they are produced by strong interaction. The K^0 and $\bar{K}^0$ only differ by strangeness, but strangeness can be changed by flavor changing process(weak interaction), namely $K^0 - \bar{K}^0$ mixing or oscillation.



$K^0 - \bar{K}^0$ Flavor eigenstate → Have definite quark components and *S*

$K_1 - K_2$ *CP* eigenstate → Have definite *CP*

$K_S - K_L$ Mass eigenstate → Have definite mass and lifetime

The *CP* eigenstates can be defined by $K^0, \bar{K}^0$ basis:

$$|K_1\rangle = \frac{1}{\sqrt{2}}[\,|K^0\rangle + |\bar{K}^0\rangle], \text{ with } CP = 1$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}[\,|K^0\rangle - |\bar{K}^0\rangle], \text{ with } CP = -1 \quad (1)$$

The K_S and K_L are kaon states with well defined mass and lifetimes that exist in nature. The *CP* symmetry is violated in weak interaction[1-3]. The $K_S - K_L$ system can be expressed as[4]:

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon_S|^2}}(\,|K_1\rangle + \epsilon_S\,|K_2\rangle)$$
$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon_L|^2}}(\,|K_2\rangle + \epsilon_L\,|K_1\rangle) \quad (2)$$

where $\epsilon_S = \epsilon + \delta$ and $\epsilon_L = \epsilon - \delta$ are complex parameters indicating possible $CP(\epsilon)$ and $CPT(\delta)$ violation. It is convenient to introduce the *CP* violation parameters in the neutral kaon sector:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = |\eta_{+-}|e^{\phi_{+-}} \cong \epsilon + \epsilon' \quad (3)$$

At present, the PDG average value of the above *CP* violation parameters are[5]:

$$|\eta_{+-}| = (2.232 \pm 0.011)\cdot 10^{-3};\ \ \phi_{+-} = (43.4 \pm 0.5)^\circ$$
$$|\epsilon| = (2.228 \pm 0.011)\cdot 10^{-3};\ \ \phi_{\epsilon} = (43.5 \pm 0.5)^\circ$$

STCF

Super tau-charm factory(STCF) is a symmetrical electron-positron collider with a peak luminosity of $\sim 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at center-of-mass energy $\sqrt{s} = 4.0$ GeV. The STCF will operate at the energies $\sqrt{s}$ from 2.0 to 7.0 GeV, which will provide 1 trillion J/ψ events per year[6,7].

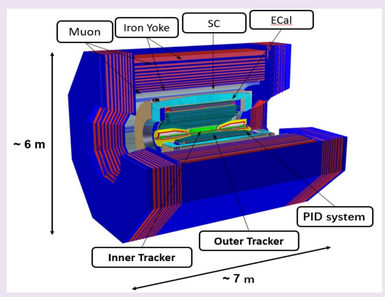


FIG.1. Schematic diagram of STCF detector

ITK: ~0.15% X_0 / layer σ_{xy}~50 μm
MDC: σ_{xy}~130 μm σ_p/p~0.5%@1GeV/c dE/dx~6%
PID: $\pi K(Kp)$ 3~4 σ separation up to 2 GeV/c
EMC: range 0.02~2GeV σ_E@1GeV: 2.5% in barrel, 4% at endcaps
MUD: 0.4~1.8GeV, π suppression > 30

ANALYSIS METHOD

The method we suggest is using the charged-conjugate particles K^0 and $\bar{K}^0$ produced in J/ψ decays. Initially pure K^0 and $\bar{K}^0$ states are produced by decay channels: $J/\psi \to K^0K^-\pi^+ / \bar{K}^0K^+\pi^-$. The *CP* violation parameters $|\eta_{+-}|$ and its phase ϕ_{+-} can be estimated by measuring the difference of time-dependent decay rates between K^0 and $\bar{K}^0$. The decay rate $R_f(\tau) \equiv R[K^0_{t=0} \to f_{t=\tau}]$ and $\bar{R}_f(\tau) \equiv R[\bar{K}^0_{t=0} \to f_{t=\tau}]$ ($f = 2\pi$ or 3π)can be written as[4]:

$$R_f(\tau)/\bar{R}_f(\tau) = \frac{[1 \mp 2\mathrm{Re}(\epsilon_L)]}{2}\Gamma_S^f \times [e^{-\Gamma_S\tau} + |\eta_f|^2 e^{-\Gamma_L\tau} \pm 2|\eta_f|e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\tau}\cos(\Delta m\tau - \phi_f)] \quad (4)$$

- Γ_S^f: partial width of $K_S \to f$
- Γ_S and Γ_L: the total width of K_S and K_L
- $\Delta m = m_L - m_S$: mass difference between K_S and K_L

The decay rate asymmetry can be formed by the combination of R_f and $\bar{R}_f$:

$$A_{CP}^f(\tau) = \frac{\bar{R}_f(\tau) - R_f(\tau)}{\bar{R}_f(\tau) + R_f(\tau)} = 2\mathrm{Re}(\epsilon_L) - 2\frac{|\eta_f|e^{\frac{1}{2}(\Gamma_S-\Gamma_L)\tau}\cos(\Delta m\tau - \phi_f)}{1 + |\eta_f|^2 e^{(\Gamma_S-\Gamma_L)\tau}} \quad (5)$$

The strategy of measuring the decay lifetime of neutral kaon at STCF is shown in Fig. 2

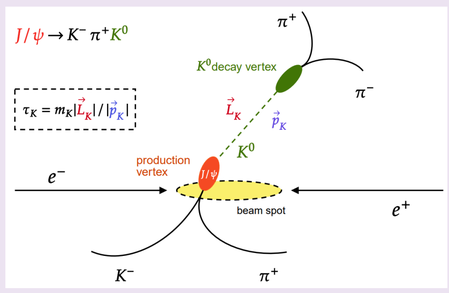


FIG.2. A diagram of how to measure the decay lifetime of $K^0/\bar{K}^0$

- Production vertex: obtained from $K^-\pi^+$ vertex fit. The position uncertainty is: $\sigma_x = 13.6\ \mu$m, $\sigma_y = 1.4\ \mu$m, $\sigma_z = 50\ \mu$m[6,7]
- Decay vertex: obtained from $\pi^+\pi^-$ vertex fit
- The proper time of neutral kaon is calculated by decay length l_K and momentum p_K:

$$t = \frac{m_{K^0} \times l_K}{p_K} \quad (6)$$

MONTE CARLO SIMULATION

A Monte Carlo(MC) simulation is performed on the basis of the total number 3.9×10^9 $J/\psi \to K^-\pi^+K^0(K^0 \to \pi^+\pi^-) + c.c.$ events. The detector resolution of K^0 decay vertex versus decay length l_K and momentum p_K is shown in Fig. 3. The detector resolution for K^0 momentum p_K is estimated to be $\sigma_{p_K}/p_K \approx 0.5\%$. The MC simulation is generated with the considerations of the position uncertainty of e^+e^- interaction point and $\pi^+\pi^-$ vertex reconstruction as well as the uncertainties of momentum reconstruction of π^+/π^-. The time dependent decay rates of $K^0(\bar{K}^0) \to \pi^+\pi^-$ are simulated based on Eq. 4 with the input parameters fixed to PDG average values.

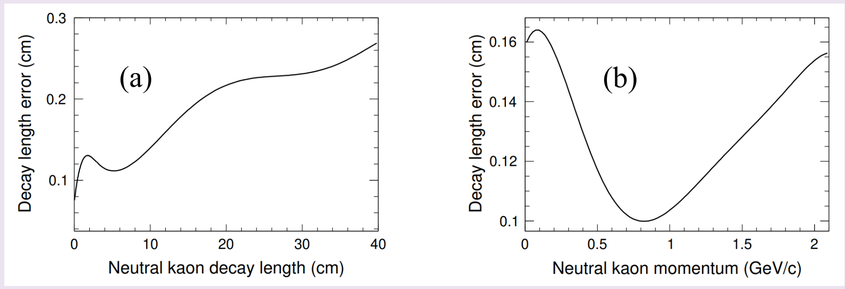


FIG.3. The detector resolution of K^0 decay vertex versus (a) decay length l_K and (b) momentum p_K

RESULTS AND SUMMARY

From the MC simulation, the time dependent number $N(\tau)$ for $K^0 \to \pi^+\pi^-$ as well as $\bar{N}(\tau)$ for $\bar{K}^0 \to \pi^+\pi^-$ are shown in Fig. 4(a), and the fitting results of time-dependent decay rate asymmetry A_{+-} are shown in Fig. 4(b). The comparison between PDG average value and fitting results are shown in Tab I. The first uncertainty of fitted parameters is statistical uncertainty, and the second is associated with the uncertainties of e^+e^- interaction point and the reconstruction of $\pi^+\pi^-$ vertex and momentum. The fitting quality is present by $\chi^2/\mathrm{d.o.f.} = 0.7$. To summarize, by using about 10^{12} J/ψ events collected at STCF, the relative accuracy in measuring the parameters $|\eta_{+-}|$ and ϕ_{+-} will be several times better than the existing measurements.

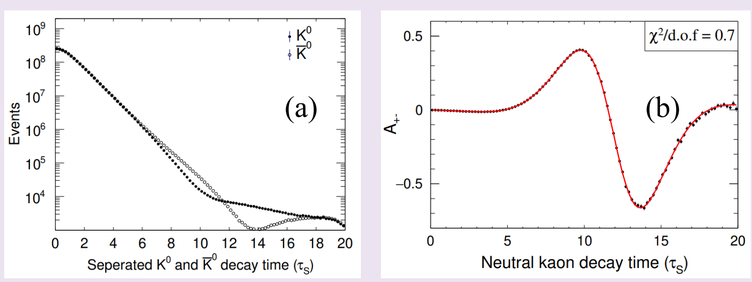


FIG.4. (a) $N(\tau)$, $\bar{N}(\tau)$ and (b) A_{+-} versus the neutral kaon decay time. The points with error bar are from MC simulation and the solid line is the fitting results.

TABLE I. The comparison between PDG average value and fitting results in this work.

Par.	$\lvert\eta_{+-}\rvert(10^{-3})$	ϕ_{+-}(degree)
PDG	2.232 ± 0.011	43.4 ± 0.5
STCF	$2.2320 \pm 0.0025 \pm 0.0027$	$43.510 \pm 0.051 \pm 0.059$

REFERENCES

[1] Phys. Rev. Lett. 10, 531 (1963)
[2] Prog. Theor. Phys. 49, 652 (1973)
[3] Phys. Rev. Lett. 13, 138 (1964)
[4] Phys. Rept. 374, 165 (2003)
[5] PTEP 2020, 083C01 (2020)
[6] Physics 49, 513 (2020)
[7] PoS CHARM2020, 007 (2021)
* J. Y. Zhang, C. D. Fu, H. B. Li, L. Liu, X. R. Zhou, Measurement of CP violation of neutral kaon system in J/ψ decay at the Super Tau-Charm Factory, in preparation