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About detecting CP-violating processes in $J/\psi \rightarrow K^0\bar{K}^0$ decay[*]

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Abstract Questions about detecting the CP-violating decay process of $J/\psi \rightarrow K^0\bar{K}^0 \rightarrow K_S K_S$ are discussed. Possible background and material regeneration effects are analyzed. The discussion can be directly extended to other vector quarkonium decays, like Υ, $\psi(2S)$ and $\phi \rightarrow K_S K_S$.

Key words CP-violation, quarkonium, regeneration, J/ψ decay, BES

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1 Introduction

If CP symmetry were conserved, the weak eigenstates of neutral kaons K_S and K_L would have definite CP quantum number, and the CP quantum number of the neutral kaon system $|K_S K_S\rangle$ and/or $|K_L K_L\rangle$ would be $CP = (-1)^l$, where l is the relative orbital angular momentum of the two-kaon pair. If the vector charmonium J/ψ can decay to $|K_S K_S\rangle$ and $|K_L K_L\rangle$, the orbital angular momentum l of the kaon pair should be $l = 1$ because of the angular momentum conservation. Hence the kaon pair from J/ψ decay should have $CP = -1$. On the other hand, the quantum number of J/ψ is $J^{PC} = 1^{--}$, so its CP quantum number is $CP = +1$. Therefore the decay of $J/\psi \rightarrow K_S K_S$ or $K_L K_L$ is a CP-violating process.

In 1980s the upper limit of the branching ratio of $J/\psi \rightarrow K_S K_S$ was set by Mark III: $Br(J/\psi \rightarrow K_S K_S) < 5.2 \times 10^{-6}$[1]. In 2004 the BESII Collaboration gave a new upper limit at 95% C.L.: $Br(J/\psi \rightarrow K_S K_S) < 1.0 \times 10^{-6}$[2] . In principle a vector particle is forbidden to decay to two identical Bosons by Bose-Einstein statistics. However for the neutral kaon system, the decay $J/\psi \rightarrow K_S K_S$ is possible due to the time-evolution effect of the neutral kaon system[3]. That is, the neutral kaon pair $K^0\bar{K}^0$ is produced at first in J/ψ decay. Then, the kaons evolve into either K_S or K_L as time goes on. If one neutral kaon appears as a K_S at any time t_1, the possibility for the other to be also a K_S at a different time t_2 is not zero, provided CP symmetry is violated, the weak eigenstates of neutral kaon system K_S and K_L are not orthogonal, $\langle K_S|K_L\rangle = |p|^2 - |q|^2 \neq 0$. We have studied this effect in a recent work[3]. We considered the time-dependent decay process

$$J/\psi \rightarrow K^0\bar{K}^0 \rightarrow K_S(t_1)K_S(t_2). \qquad (1)$$

The time-integrated branching fraction of $J/\psi \rightarrow K_S K_S$ obtained by us is $Br(J/\psi \rightarrow K_S K_S) = (1.94 \pm 0.20) \times 10^{-9}$. Although the existence of the neutral kaon pair $K_S(t_1)K_S(t_2)$ at different time is not forbidden by the spin-statistics, there is still a question left. The mean lifetime of K_S is short, when it is produced, it decays quickly into two pions. The pions can fly into the detector. In experiment K_S is reconstructed by the two-pion event recorded in the detector. The two pion-pairs from $K_S(t_1)$ and $K_S(t_2)$ can exist simultaneously for a while so that they can be detected by the detector. However the existence of two identical pion-pairs with relative orbital angular momentum $l = 1$ is forbidden by Bose-Einstein statistics. Therefore the process $J/\psi \rightarrow K^0\bar{K}^0 \rightarrow K_S(t_1)K_S(t_2) \rightarrow 2(\pi^+\pi^-)$ can still not

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happen if the invariant masses of two-pion pairs are identical. Although the masses of the two-pion pairs may be slightly different according to the probability density function of the $\mathrm{K_S}$ decays, they are still highly suppressed by spin-statistics. In this paper, we will discuss the possible contamination from $\mathrm{K_L} \to \pi\pi$ decay, and the background of the regeneration effect of $\mathrm{K_L} \to \mathrm{K_S}$ in matter when the neutral kaons produced in J/ψ decay pass through the beam pipe.

Both MarkⅢ and BESⅡ collaborations used $2(\pi^+\pi^-)$ to search for J/ψ and $\psi(2S) \to \mathrm{K_S K_S}$ decays[1, 2]. As mentioned above, the decay mode $\mathrm{J}/\psi \to \mathrm{K_S}(t_1)\mathrm{K_S}(t_2) \to 2(\pi^+\pi^-)$ is forbidden by Bose-Einstein statistics. Therefore the possibility is quite small to search for $\mathrm{J}/\psi \to \mathrm{K_S K_S}$ with a $2(\pi^+\pi^-)$ in the final state in experiment. If one reconstructs $\mathrm{K_S}$ with $\pi^+\pi^-$, the other with $\pi^0\pi^0$, the situation will change. The chain process

$$\mathrm{J}/\psi \to \mathrm{K_S}(t_1)\mathrm{K_S}(t_2) \to (\pi^+\pi^-)(\pi^0\pi^0) \qquad (2)$$

is not forbidden by spin-statistics. This is the correct final state to search for the *CP*-violating decay process of $\mathrm{J}/\psi \to \mathrm{K_S K_S}$.

2 Reconstruction of $\mathrm{K_S}$ decay length of at BES-Ⅲ

In experiment $\mathrm{K_S}$ is reconstructed by its two-pion decays. In general this is a good reconstruction method, because $\mathrm{K_S}$ dominantly decays to $\pi\pi$ with the possibility of almost 100%, while the $\mathrm{K_L} \to \pi\pi$ decay is only a rare process which violates *CP* symmetry[4]. The total branching ratio of $\mathrm{K_L} \to (\pi^+\pi^- + \pi^0\pi^0)$ is only $(2.983 \pm 0.038) \times 10^{-3}$[5]. However, for detecting the $\mathrm{J}/\psi \to \mathrm{K_S K_S}$ decay, the $\mathrm{J}/\psi \to \mathrm{K_S K_L}$ ($\mathrm{K_L} \to \pi\pi$) decay may cause a sizable contamination. As we have calculated previously, the branching ratio of $\mathrm{J}/\psi \to \mathrm{K_S K_S}$ is $Br(\mathrm{J}/\psi \to \mathrm{K_S K_S}) = (1.94 \pm 0.20) \times 10^{-9}$[3]. The branching ratio of $\mathrm{J}/\psi \to \mathrm{K_S K_L}$ measured by experiment is $Br(\mathrm{J}/\psi \to \mathrm{K_S K_L}) = (1.82 \pm 0.04 \pm 0.13) \times 10^{-4}$[6], which is 10^5 times larger than that of $\mathrm{J}/\psi \to \mathrm{K_S K_S}$, therefore even a small fraction of $\mathrm{K_L}$'s decays into $\pi\pi$ can cause large contaminations to the measurement of $\mathrm{J}/\psi \to \mathrm{K_S K_S}$, because both of the two processes can be tagged by a 4-pion final state in this case.

The integrated decay probability for a particle of mean lifetime τ at any time t in the rest frame of this particle is

$$P_{\mathrm{T}}(t) = 1 - \mathrm{e}^{-t/\tau} \ . \qquad (3)$$

We can transform this decay probability into the laboratory frame, where the particle moves with the three-momentum p, and change the variable to be the length of the path along which the particle travels, x,

$$P(x) = 1 - \mathrm{e}^{mx/(p\tau c)} \ , \qquad (4)$$

where m is the mass of the particle, c is the speed of light in vacuum. The total decay probabilities of $\mathrm{K_S}$ and $\mathrm{K_L}$ at the path length x in the rest frame of J/ψ are shown in Fig. 1. Within the length of 0.4 m almost 100% of the $\mathrm{K_S}$'s decayed, while only 0.87% of the $\mathrm{K_L}$'s decayed within this length. The decay chain $\mathrm{J}/\psi \to \mathrm{K_S K_L} \to 2(\pi\pi)$ at short decay length may be falsely reconstructed as $\mathrm{J}/\psi \to \mathrm{K_S K_S} \to 2(\pi\pi)$, which is a contamination for the measurement of $\mathrm{J}/\psi \to \mathrm{K_S K_S}$ decay. The contamination from $\mathrm{J}/\psi \to \mathrm{K_S K_L}$ with successive $\mathrm{K_L} \to \pi\pi$ can be defined by

$$\begin{aligned} E_{\mathrm{K_L}}(x) \equiv\ & Br(\mathrm{J}/\psi \to \mathrm{K_S K_L} \to \\ & (\pi^+\pi^-)(\pi^0\pi^0))_{|\text{at length } x} = \\ & Br(\mathrm{J}/\psi \to \mathrm{K_S K_L}) \times P_{\mathrm{K_S}}(x) \times P_{\mathrm{K_L}}(x) \times \\ & \big[Br(\mathrm{K_S} \to \pi^+\pi^-)Br(\mathrm{K_L} \to \pi^0\pi^0) + \\ & Br(\mathrm{K_S} \to \pi^0\pi^0)Br(\mathrm{K_L} \to \pi^+\pi^-)\big], \qquad (5) \end{aligned}$$

where $P_{\mathrm{K_S}}(x)$ and $P_{\mathrm{K_L}}(x)$ are respectively the decay probabilities of $\mathrm{K_S}$ and $\mathrm{K_L}$ at length x, which are obtained by substituting the relative quantities of $\mathrm{K_S}$ and $\mathrm{K_L}$ into Eq. (4). The function $E_{\mathrm{K_L}}(x)$ is shown in Fig. 2. At $x = 0.4$ m the branching ratio of the successive decay $\mathrm{J}/\psi \to \mathrm{K_S K_L} \to (\pi^+\pi^-)(\pi^0\pi^0)$ is about 2.0×10^{-9}, which is at the same order as the $\mathrm{J}/\psi \to \mathrm{K_S K_S}$ ($\to (\pi^+\pi^-)(\pi^0\pi^0)$) decay. This is a large

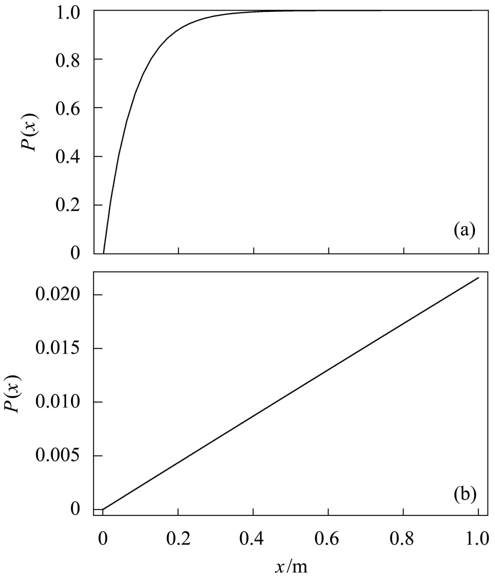

Fig. 1. Integrated decay probabilities of $\mathrm{K_S}$ and $\mathrm{K_L}$ produced from J/ψ decay in the rest frame of J/ψ. (a) Total decay probability for $\mathrm{K_S}$ at x; (b) Total decay probability for $\mathrm{K_L}$ at x.

background for searching for K_SK_S events, which should be subtracted. In experiment the $J/\psi \rightarrow K_SK_S$ decay should be measured by reconstructing the $(\pi^+\pi^-)(\pi^0\pi^0)$ events, then subtracting the contribution of the $J/\psi \rightarrow K_SK_L \rightarrow (\pi^+\pi^-)(\pi^0\pi^0)$ decay.

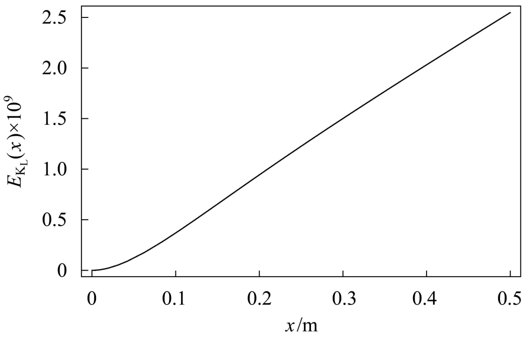

Fig. 2. Branching ratio of $J/\psi \rightarrow K_SK_L \rightarrow (\pi^+\pi^-)(\pi^0\pi^0)$ at decay length x in the rest frame of J/ψ.

3 Effect of kaon regeneration

To analyze the tiny CP-violating process, one has to take properly into account the effects of decoherence due to the matter effects in an environment that is not the perfect vacuum in which the kaon system evolves, it entails a pure kaon state to convert into a mixed one. These are effects that exist in addition to the weak interactions and are dominated by the strong interactions of the kaons with the environment. Two kinds of regeneration happen within the detectors: coherent regeneration and incoherent regeneration. The second one is associated with a nucleus recoiling in the material[7]. In general, the angle between the directions of the incident and outgoing kaons is zero for the coherent regeneration, while it is non-zero for the incoherent case making it distinguishable from the signal. Knowing the difference Δf between the forward scattering amplitudes of K^0 and $\bar{K}^0$ by the atoms, the mean lifetime τ_s of the K_S, the kaon mass m, the $K_L - K_S$ mass difference Δm, and the time t taken by the kaon in its own rest frame to traverse the regenerator, one can predict the probability P_{regen} for a K_S regenerated from an original K_L coherently[8]:

$$P_{\text{regen}}(K_L \rightarrow K_S) = |\rho|^2 e^{-2\nu l \sigma_{\text{tot}}} , \tag{6}$$

where σ_{tot} is the total absorption cross section, ν the atomic density, and l the thickness of the regenerator, and ρ is defined as[8]:

$$\rho = \frac{\pi\nu}{1/(2\tau_s) - i\Delta m}\frac{\Delta f}{m}\kappa , \tag{7}$$

and

$$\kappa = 1 - e^{(-1/(2\tau_s)+i\Delta m)t} . \tag{8}$$

At BES-III, the $K_L \rightarrow K_S$ or $K_S \rightarrow K_L$ regeneration can happen in the matter of the beam pipe and in the inner wall of the main draft chamber. According to the design report of BES-III[9], the beam pipe is 1.3 mm of Beryllium, at the radius of 32 mm away from the beam axis. The inner wall of the main draft chamber is about 1.2 mm thick Carbon, at the radius of 59 mm. The matter in the detector is assumed to be perfectly symmetric. According to the predictions of Quantum Mechanics, the K_SK_S events from coherent regeneration should be zero because of the 100% destructive interference between K_S and K_L if both neutral kaons go through identical amount of material. However, if the K_S decays before entering the material in the detector, then K_L will cross the material as a free particle. In this case, the K_SK_S will be generated with full strength of the regeneration effect[7]. The probability of the regeneration is very small (order of 10^{-5} according to Ref. [7]). However the branching fraction of $J/\psi \rightarrow K_LK_S$ is about 10^5 times larger than that of K_SK_S production[3], the contamination from $K_L \rightarrow K_S$ regeneration is about

$$\begin{aligned} E_{\text{regen}} \equiv\ & Br(J/\psi \rightarrow K_SK_L \rightarrow 2(\pi\pi)) = \\ & Br(J/\psi \rightarrow K_SK_L) \times P_{\text{regen}}(K_L \rightarrow K_S) \sim \\ & (1.82 \times 10^{-9}) . \end{aligned} \tag{9}$$

It is of the same order as the signal $J/\psi \rightarrow K_SK_S$. Experimentally, one can employ the decay length and angular distribution of the K_S to distinguish the signal event from this kind of background.

One more remark is the following. Soft photons can be emitted from the initial and final states in vector quarkonia to $K\bar{K}$ decays. The radiation of the soft photons in the decays allows the $K^0\bar{K}^0$ in a $C = +1$ state. Such a process with a soft photon in the K_SK_S or K_LK_L final state is not CP-violating. The detection of the soft photons depends on the sensitivity of the detectors. Therefore the soft-photon-radiation process is an experimental background for this analysis. This background should be subtracted in experiment.

It is interesting to study the Δt distribution to separate the K_SK_S events from the K_SK_L background. The weak eigenstates of the K^0–$\bar{K}^0$ system are $|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$ and $|K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle$ with eigenvalues $\mu_S = m_S - \frac{i}{2}\Gamma_S$ and $\mu_L = m_L - \frac{i}{2}\Gamma_L$, respectively, where the m_S and Γ_S (m_L and Γ_L) are the mass and width of K_S (K_L) meson. Following the $J/\psi \rightarrow K^0\bar{K}^0$

decay, the K^0 and $\bar{K}^0$ will go separately and the time-evolution of the particle states $|K^0(t)\rangle$ and $|\bar{K}^0(t)\rangle$ are given by $|K^0(t)\rangle = \frac{1}{2p}\left(e^{-i\mu_S t}|K_S\rangle + e^{-i\mu_L t}|K_L\rangle\right)$ and $|\bar{K}^0(t)\rangle = \frac{1}{2q}\left(e^{-i\mu_S t}|K_S\rangle - e^{-i\mu_L t}|K_L\rangle\right)$, respectively. Then the amplitudes to find the K_SK_S and K_SK_L are given by[3]

$$A_1(t_1,t_2) \equiv \langle K_SK_S|K^0\bar{K}^0(t_1,t_2)\rangle^{C=-1} = \frac{1}{2\sqrt{2}pq}\left[(|p|^2-|q|^2)(g_{LS}-g_{SL})\right], \quad (10)$$

$$A_2(t_1,t_2) \equiv \langle K_SK_L|K^0\bar{K}^0(t_1,t_2)\rangle^{C=-1} = \frac{1}{2\sqrt{2}pq}\left[g_{LS}-(|p|^2-|q|^2)^2 g_{SL}\right], \quad (11)$$

where $g_{LS} = e^{-i\mu_L t_1 - i\mu_S t_2}$ and $g_{SL} = e^{-i\mu_S t_1 - i\mu_L t_2}$. Since the states $|K_S\rangle$ and $|K_L\rangle$ are non-orthogonal, we have $\langle K_S|K_L\rangle = \langle K_L|K_S\rangle = |p|^2-|q|^2$ and $\langle K_S|K_S\rangle = \langle K_L|K_L\rangle = 1$. Squaring the amplitudes $A_1(t_1,t_2)$ and $A_2(t_1,t_2)$, one can get the time-dependent probabilities to find K_SK_S and K_SK_L pairs

$$\frac{d^2\mathcal{P}[K_S(t_1),K_S(t_2)]}{dt_1dt_2} \propto |A_1(t_1,t_2)|^2 = \frac{(|p|^2-|q|^2)^2}{4|pq|^2}e^{-\Gamma(t_1+t_2)}[\cosh(y\Gamma(t_2-t_1)- \cos(x\Gamma(t_2-t_1)], \quad (12)$$

$$\frac{d^2\mathcal{P}[K_L(t_1),K_S(t_2)]}{dt_1dt_2} \propto |A_2(t_1,t_2)|^2 = \frac{1}{8|pq|^2}e^{-\Gamma(t_1+t_2)}[e^{y\Gamma(t_2-t_1)} - 2(|p|^2-|q|^2)^2 \times \cos(x\Gamma(t_2-t_1)) + (|p|^2-|q|^2)^4 e^{-y\Gamma(t_2-t_1)}], \quad (13)$$

where $\Gamma = \frac{\Gamma_S+\Gamma_L}{2}$, $x=\frac{\Delta m}{\Gamma}$ and $y=\frac{\Delta\Gamma}{2\Gamma}$ (Δm is the mass difference of K_L and K_S, i.e., $\Delta m = m_L - m_S$, while $\Delta\Gamma = \Gamma_L - \Gamma_S$ is the width difference).

We then integrated Eqs. (12) and (13) over the sum t_1+t_2 for fixed $\Delta t = t_2 - t_1$, and get

$$\mathcal{P}[K_SK_S](\Delta t) \propto \frac{(|p|^2-|q|^2)^2}{4|pq|^2} \times [\cosh(y\Gamma(\Delta t) - \cos(x\Gamma(\Delta t)], \quad (14)$$

$$\mathcal{P}[K_LK_S](\Delta t) \propto \frac{1}{8|pq|^2}[e^{y\Gamma(\Delta t)} - 2(|p|^2-|q|^2)^2 \times \cos(x\Gamma(\Delta t)) + (|p|^2-|q|^2)^4 e^{-y\Gamma(\Delta t)}]. \quad (15)$$

The above time-dependent probabilities to observe K_SK_S and K_SK_L pairs, can be used to model the signal Δt distributions. It will be interesting for the KLEO[10] experiment to do a time-dependent analysis in $\phi \to K_SK_S$ and K_SK_L by reconstructing both neutral kaons from $(\pi^+\pi^-)(\pi^0\pi^0)$ final states with high statistics.

4 Conclusion

In conclusion, we have pointed out that $(\pi^+\pi^-)(\pi^0\pi^0)$ final state should be used for measuring the $J/\psi \to K_SK_S$ decay. The contamination of the successive process $J/\psi \to K_SK_L \to 2(\pi\pi)$ is large, which should be subtracted from the data of the $J/\psi \to (K_SK_L + K_SK_S) \to 2(\pi\pi)$ decay. We also discussed the background of regeneration effects of $K_L \to K_S$ in matter when the neutral kaon passes through the beam pipe. All results here can be extended to the $\phi \to K^0\bar{K}^0$ decay. Finally, the time-dependent signal models are calculated.

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