Search for the $CP$-violating decays $\Upsilon(4S) \to B^0 \bar{B}^0 \to J/\psi K^0_S + J/\psi (\eta_c) K^0_S$

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$CP$ violation has been established in the neutral kaon system [1] and the neutral $B$ meson system [2]. In the standard model (SM) Kobayashi-Maskawa theory, it arises from an irreducible phase in the weak interaction quark-mixing matrix [3]. This theory predicts that $CP$ violation in the $Y(4S)$ system should also exist.

In the decay $Y(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_1f_2$, where $f_1$ and $f_2$ are $CP$ eigenstates, the $CP$ eigenvalue of the final state $f_1f_2$ is $\xi = -\xi_1\xi_2$. Here the minus sign corresponds to odd parity from the angular momentum between $f_1$ and $f_2$. If $f_1$ and $f_2$ have the same $CP$ eigenvalue, i.e. $(\xi_1,\xi_2) = (+1,+1)$ or $(-1,-1)$, $\xi$ is equal to $-1$. Such decays, for example $(f_1,f_2) = (J/\psi K_0^0, J/\psi K_0^0)$, violate $CP$ conservation since the $Y(4S)$ meson has $J_{PC} = 1^{--}$ and thus has $\xi_{Y(4S)} = +1$. The branching fraction within the SM is

$$B( Y(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_1f_2 ) = F \cdot B(Y(4S) \rightarrow B^0\bar{B}^0)B(B^0 \rightarrow f_1)B(\bar{B}^0 \rightarrow f_2),$$

where $F$ is a suppression factor due to $CP$ violation. The factor $F$ can be calculated in terms of mixing and $CP$ violating parameters [4],

$$F \simeq \frac{x^2}{1+x^2}(2\sin 2\phi_1)^2$$

$$= 0.68 \pm 0.05,$$

where $x = \Delta m_d/\Gamma = 0.776 \pm 0.008$ [5], $\Delta m_d$ is the $B^0$ mixing parameter, $\Gamma$ is the average decay width of the neutral $B$ meson. The angle $\phi_1$ is one of the three interior angles of the unitarity triangle of the quark-mixing matrix, and $\sin 2\phi_1 = 0.675 \pm 0.026$ [6]. The effect of direct $CP$ violation is neglected in this formula. The same expression also holds for the case in which $f_1$ and $f_2$ are different final states both of which are governed by $b \rightarrow c\bar{c}\bar{s}$ transitions; examples include $\eta_s K_0^0$, $\psi(2S)K_0^0$ and $\chi_{c1}K_0^0$.

In this Letter, we present the first search for $CP$ violating decays of the $Y(4S)$. The data sample used contains 535 million $Y(4S)$ mesons collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. A partial reconstruction technique is employed to enhance the signal sensitivity. No significant signals were observed. We obtain an upper limit of $4 \times 10^{-7}$ at the 90% confidence level for the branching fractions of the $CP$ violating modes, $Y(4S) \rightarrow B^0\bar{B}^0 \rightarrow J/\psi K_0^0 + J/\psi(\eta_s)K_0^0$. Extrapolating the result, we find that an observation with 5$\sigma$ significance is expected with a 30 ab$^{-1}$ data sample, which is within the reach of a future super $B$ factory.

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The identity of each charged track is determined by a sequence of likelihood ratios that best matches the available information. Tracks are identified as pions or kaons based on their specific ionization in the CDC as well as the TOF and ACC responses. This classification is superseded if the track is identified as a lepton: electrons are identified by the presence of a matching ECL cluster with energy and transverse profile consistent with an electromagnetic shower; muons are identified by their range and transverse scattering in the KLM.

We use $2.68 \times 10^5$ Monte Carlo (MC) simulation events for each signal category. For background MC events, we use a sample of $3.9 \times 10^{10}$ generic BB decays in which one of the $B$ mesons decays to a known $J/\psi(\mu^+\mu^- \text{ or } e^+e^-)X$ final state. For the dataset used in the present analysis, the MC simulation predicts a small signal yield, $0.04$ events, when we choose the combination $(f_1, f_2) = (J/\psi K^0_S, J/\psi K^0_S)$ and fully reconstruct both $J/\psi K^0_S$ final states. Here we use the $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ and $K^0_S \rightarrow \pi^+\pi^-$ modes. In order to increase the signal yield, we instead adopt a partial reconstruction method. We fully reconstruct one $B^0 \rightarrow J/\psi K^0_S$ decay (called $f_1 J/\psi K^0_S$ hereafter) and find another $K^0_S$ (called $\text{tag} K^0_S$ hereafter) from the remaining particles. Then we reconstruct the recoil mass ($M_{\text{recoil}}$) using $J/\psi K^0_S$ and $\text{tag} K^0_S$. The recoil mass distribution should in principle include peaks that correspond to the $\eta_c, J/\psi, \chi_{c1}$, or $\psi(2S)$. We choose two of the possible combinations, $(f_1, f_2) = (f_1 J/\psi K^0_S, J/\psi \text{tag} K^0_S)$ and $(f_1 J/\psi K^0_S, \eta_c \text{tag} K^0_S)$. In the following, these are referred to as inclusive-$J/\psi$ combinations and an inclusive-$\eta_c$ combinations, respectively. Based on a MC study, we expect that the signal yield will increase by a factor of $40$ compared to full reconstruction while maintaining a reasonable signal to background ratio $(S/B)$ of about $1/7$ for these two combinations. We do not use other combinations because the $S/B$ ratio is less than $1/100$.

We use oppositely charged track pairs to reconstruct $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ decays, where at least one track is positively identified as a lepton. Photons within $50$ mrad of the $e^+$ and $e^-$ tracks are included in the invariant mass calculation (denoted as $e^+e^-(\gamma)$). The invariant mass is required to lie in the range $-0.15 \text{ GeV/c}^2 < M_{ee(\gamma)} - m_{J/\psi} < 0.036 \text{ GeV/c}^2$ and $-0.06 \text{ GeV/c}^2 < M_{\mu\mu} - m_{J/\psi} < 0.036 \text{ GeV/c}^2$, where $m_{J/\psi}$ denotes the nominal mass of $J/\psi$, $M_{ee(\gamma)}$ and $M_{\mu\mu}$ are the reconstructed invariant masses from $e^+e^-(\gamma)$ and $\mu^+\mu^-$, respectively. Asymmetric intervals are used to include part of the radiative tails. Candidate $K^0_S \rightarrow \pi^+\pi^-$ decays are oppositely charged track pairs that have an invariant mass within $\pm 0.016 \text{ GeV/c}^2 (\pm \sigma)$ of the nominal $K^0$ mass. The $\pi^+\pi^-$ vertex is required to be displaced from the interaction point in the direction of the pion pair momentum for $\text{tag} K^0_S$. 

![FIG. 1: $M_{bc}$ (left) and $\Delta E$ (right) distributions for $B^0 \rightarrow J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)$ decay ($\ell = e, \mu$. The solid curves show the fit to signal plus background distributions, and the dashed curves show the background distributions.](image-url)

For the full reconstruction of a $B$ decay, we use the energy difference $\Delta E \equiv E_{\text{beam}} - E_{\text{CMS}}$ and the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}})^2 - (p_{B}^{\text{CMS}})^2}$, where $E_{\text{CMS}}$ is the beam energy in the center-of-mass system (cms) of the $\Upsilon(4S)$ resonance, and $p_{B}^{\text{CMS}}$ and $E_{\text{beam}}$ are the cms energy and momentum of the reconstructed $B$ candidate, respectively. The $M_{bc}$ and $\Delta E$ distributions are shown in Fig. 1. The signal is extracted from an unbinned extended maximum likelihood fit to the $M_{bc}$-\$Delta E$ distribution. The signal shape is modeled with a single (double) Gaussian while the background shape is modeled with an ARGUS function [9] (a first order polynomial) for the $M_{bc}$ (\$Delta E$) distribution. We obtain $8283 \pm 94 f_{J/\psi K^0_S}$ events when we do not require a $\text{tag} K^0_S$.

We require $5.27 \text{ GeV/c}^2 \leq M_{bc} \leq 5.29 \text{ GeV/c}^2$ and $|\Delta E| \leq 0.04 \text{ GeV}$ for $f_{J/\psi K^0_S}$. The recoil mass is calculated by combining a $f_{J/\psi K^0_S}$ candidate and a $\text{tag} K^0_S$ candidate. The expected number of signal events estimated from MC is $1.1 (0.6)$ with a reconstruction efficiency of $28.8 (26.8)$ % for the inclusive-$J/\psi$ ($\eta_c$) combination where branching fractions of sub-decays are not included. With the partial reconstruction technique, the number of $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ decays in the $(J/\psi K^0_S, J/\psi K^0_S)$ combination is about twice as large as that for the $(J/\psi K^0_S, \eta_c K^0_S)$ combination. A total of $1.7$ signal events are then expected in our dataset.

The dominant source of background is generic $B^0$ decays. A partially reconstructed $B$ candidate should be flavor non-specific if it is a signal event. On the other hand, about a half of the generic $B^0$ decays that survive the selection are flavor specific. In order to distinguish between the signal and the background, we therefore identify the flavor of the partially-reconstructed accompanying $B$ meson using leptons, charged pions and kaons that are not associated with the fully reconstructed $B$ meson. The procedure for flavor tagging is described in Ref. 10. We use an event-by-event flavor-tagging dilution factor, $r$, which ranges from $r = 0$ for no flavor.
discrimination to $r = 1$ for perfect flavor assignment.

We determine the signal yield by performing an unbinned extended maximum-likelihood fit to the candidate events. The likelihood function is

$$
\mathcal{L} = \frac{1}{N!} \exp \left( - \sum_k n_k \right) \prod_{i=1}^{N} \left[ \sum_k n_k f_k (M_i^{\text{recoil}}, r_i) \right],
$$

where $N$ is the total number of candidate events, $n_k$ is the number of events and $f_k$ is the probability density function (PDF) for each event category $k$, which is inclusive-$J/\psi$, inclusive-$\eta_c$ or background. The parameters $M_i^{\text{recoil}}$ and $r_i$ are the recoil mass and $r$ value for the $i$-th event. The PDFs are obtained from the MC simulation. The recoil mass distributions are modeled with a triple Gaussian for each signal mode and an exponential shape for background. We do not find any peaking background in either the MC samples or in the $M_{bc}$ sideband data. The PDFs for the $r$ distributions are histograms with 10 bins obtained from MC. The ratio between the inclusive-$J/\psi$ and $\eta_c$ signals is fixed from the MC.

We check the method using charged $B$ decay control samples, $\Upsilon(4S) \rightarrow B^+ B^- \rightarrow (f_{B^+}, J/\psi \pi \pi K^+ \eta_c)$, where $f_{B^+}$ stands for $J/\psi(e^+ e^- , \mu^+ \mu^-)K^+$ and $D^0(K^{+}\pi^-, K^{+}\pi^-\pi^+\pi^-)\pi^+$ decays [11]. Figure 2 shows the recoil mass distribution for the charged $B$ control samples. The fit yields 206\pm57 signal events, which is in good agreement with the MC expectation (183 events). If we float the ratio between the inclusive-$J/\psi$ and $\eta_c$ modes, we obtain 96\pm23 and 109\pm25 events for the inclusive-$J/\psi$ and $\eta_c$ modes, respectively. These results are also consistent with the MC expectation, 90 (93) events for inclusive-$J/\psi$ ($\eta_c$) mode. We obtain correction factors, the mean and width for the signal peaks and the slope for background, by fitting these samples.

We adopted a blind analysis method and estimated systematic uncertainties before obtaining the final result. The systematic uncertainties for the combined branching fraction, $B (\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow J/\psi \eta_c K^0_S)$, are summarized in Table 1. The dominant source of systematics is due to the uncertainties in the correction factors for the recoil mass distribution; we assign 20.5\%, which is the sum in quadrature of 19.7\% from the signal shapes and 5.5\% from the background shape.

### Table 1: Systematic uncertainties in the branching fraction measurement

| Source                          | (%)   |
|---------------------------------|-------|
| Recoil mass distribution        | 20.5  |
| $r$ distribution                | 4.2   |
| Reconstruction efficiency       | 5.7   |
| Number of $BB$ pairs            | 1.3   |
| Branching fractions of sub-decays | 10.9  |
| **Total**                       | **24.3** |

Possible differences between data and the MC in the $r$ distributions are also studied. We use neutral $B$ decay control samples, $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow (f_{B^0} , (J/\psi, \eta_c) \pi \pi K^0_S)$, decays, where $f_{B^0}$ represents $B^0 \rightarrow D^{(*)-} \pi^+$ and $D^{*-} \pi^+$ followed by the decays $D^{*-} \rightarrow \bar{D}^0 \pi^-, \bar{D}^0 \rightarrow K^+ \pi^-, K^+ \pi^- \pi^0, K^+ \pi^- \pi^+ \pi^-$, $D^+ \rightarrow K^+ \pi^+ \pi^-, \rho^+ \rightarrow \pi^+ \pi^0$ and $\pi^0 \rightarrow \gamma \gamma$. We obtain 35\pm16 signal events for these samples, which is consistent with the MC prediction (64 events) within two standard deviations. There is no discrepancy between data and fit results either in recoil mass or in the $r$ distributions, as shown in Fig 2. We repeat the fit using the background $r$ PDF determined from the data in the recoil mass sideband regions $M^{\text{recoil}} \in (2.40, 2.85)$ and $(3.20, 3.30)$ GeV/c$^2$. The difference between the two fit results
at the 90% confidence level, where the SM prediction is $1.4 \times 10^{-7}$. This corresponds to $F < 2$ at the 90% confidence level. We also search for $(J/\psi K_S^0, J/\psi K_S^0)$ combinations by fully reconstructing both $B$ mesons. No candidates are observed.

In summary, a search for CP violation in $\Upsilon(4S)$ decays was performed. In a data sample of 535 million $B\bar{B}$ pairs obtained via decays of the $\Upsilon(4S)$ resonance, no significant signals were observed. We obtain an upper limit of $4 \times 10^{-7}$ at the 90% confidence level for the branching fraction of the $CP$ violating modes, $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow J/\psi K_S^0 + (J/\psi, \eta_c)K_S^0$. Assuming the SM, with an integrated luminosity of 30 ab$^{-1}$ that is expected to be available in a future $B$ factory, these decays can be observed with $5\sigma$ significance.

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