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

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Abstract. We report the first search for $CP$ violating decays of the $\Upsilon(4S)$ using a data sample that contains 535 million $\Upsilon(4S)$ mesons 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, $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow J/\psi K^0_S + J/\psi(\eta_c)K^0_S$. 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.

1. Introduction

$CP$ 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 $\Upsilon(4S)$ system should also exist.

In the decay $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_1f_2$, 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 $(f_1, f_2) = (J/\psi K^0_S, J/\psi(\eta_c)K^0_S)$, violate $CP$ conservation since the $\Upsilon(4S)$ meson has $J^{PC} = 1^{--}$ and thus has $\xi_{\Upsilon(4S)} = +1$. The branching fraction within the SM is

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

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 $\sin 2\phi_1 = 0.675 \pm 0.026$ [5]. 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 $b \rightarrow c\bar{c}s$ transitions; examples include $\eta_c K^0_S$, $\psi(2S)K^0_S$ and $\chi_{c1}K^0_S$. 
2. Analysis

We present the first search for CP violating decays of the Υ(4S). The data sample used contains 535 million Υ(4S) mesons collected with the Belle detector [7] at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [6]. We also 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 $B\bar{B}$ decays in which one of the $B$ mesons decays to a known $J/\psi(\mu^+\mu^-)$ 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 $f_{J/\psi K^0_S}$ hereafter) and find another $K^0_S$ (called $f_{\eta K^0_S}$ hereafter) from the remaining particles. We then reconstruct the recoil mass ($M^{\text{recoil}}$) using $J/\psi K^0_S$ and $\eta K^0_S$. 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, $(f_1, f_2) = (f_{J/\psi K^0_S}, J/\psi \eta K^0_S)$ and $(f_{J/\psi K^0_S}, J/\psi \eta\eta K^0_S)$. In the following, these are referred to as inclusive-$J/\psi$ combinations and an inclusive-$\eta$ 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.

The recoil mass is calculated by combining a $f_{J/\psi K^0_S}$ candidate and a $f_{\eta K^0_S}$ 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 $(J/\psi K^0_S, \eta K^0_S)$ 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. [8]. 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 check the method using charged $B$ decay control samples, $\Upsilon(4S) \rightarrow B^+B^- \rightarrow f_{B^+} + J/\psi(\eta_c)\eta K^-$, where $f_{B^+}$ stands for $J/\psi(e^+e^-, \mu^+\mu^-)K^+$ and $D^0(K^+\pi^-, K^+\pi^-\pi^+)\pi^+$ decays [9]. Figure 1 shows the recoil mass distribution for the charged $B$ control samples. The fit yields $206 \pm 57$ signal events, which is in good agreement with the MC expectation (183 events). 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. Total systematic uncertainties for the combined branching fraction, $B(\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow J/\psi K^0_S, (J/\psi, \eta_c) K^0_S)$, is 24.4%. 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.

The results of the final fit are shown in Fig. 1. The extracted signal yield, $-1.5^{+3.6}_{-2.8}$ events, is consistent with zero as well as with the SM prediction (1.7 events). An upper limit is determined with a frequentist method [10], where the PDFs are smeared to include systematic uncertainties. We obtain $B(\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow J/\psi K^0_S, (J/\psi, \eta_c) K^0_S) < 4 \times 10^{-7}$ at the 90 % confidence level,
Figure 1. Recoil mass distribution for the charged $B$ decay control samples (left), recoil mass (middle) and $r$ (bottom) distribution for samples reconstructed as $\Upsilon(4S) \to (J/\psi K^0_S, J/\psi, \eta_c K^0_S)$ decay. The solid lines show the fits to signal plus background distributions while the dashed lines show the background distributions.

where the SM prediction is $1.4 \times 10^{-7}$. We also search for $(J/\psi K^0_S, J/\psi K^0_S)$ combinations by fully reconstructing both $B$ mesons. No candidates are observed.

3. Summary
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, $\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K^0_S + (J/\psi, \eta_c) K^0_S$. 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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