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Search for the *CP*-Violating Decays $\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K_S^0 + J/\psi(\eta_c)K_S^0$

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0031-9007/07/99(21)/211601(5)

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We report the first search for *CP*-violating decays of the $\Upsilon(4S)$ using a data sample that contains 535×10^6 $\Upsilon(4S)$ 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 4×10^{-7} at the 90% confidence level for the branching fractions of the *CP* violating modes, $\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K_S^0 + J/\psi(\eta_c)K_S^0$. Extrapolating the result, we find that an observation with 5σ 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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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 $\Upsilon(4S) \to B^0\bar{B}^0 \to f_1 f_2$, where f_1 and f_2 are *CP* eigenstates, the *CP* eigenvalue of the final state $f_1 f_2$ 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 $(-1, -1)$, ξ is equal to -1. Such decays, for example, $(f_1, f_2) = (J/\psi K_S^0, J/\psi K_S^0)$, 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

$$\mathcal{B}[\Upsilon(4S) \to B^0\bar{B}^0 \to f_1 f_2] = F \cdot \mathcal{B}[\Upsilon(4S) \to B^0\bar{B}^0] \times \mathcal{B}(B^0 \to f_1)\mathcal{B}(\bar{B}^0 \to f_2), \quad (1)$$

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],

$$F \simeq \frac{x^2}{1 + x^2}(2\sin 2\phi_1)^2 = 0.68 \pm 0.05, \quad (2)$$

where $x = \Delta m_d/\Gamma = 0.776 \pm 0.008$ [5], Δm_d is the B^0 mixing parameter, and Γ is the average decay width of the neutral B meson. The angle ϕ_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 $b \to c\bar{c}s$ transitions; examples include $\eta_c K_S^0$, $\psi(2S)K_S^0$, and $\chi_{c1}K_S^0$.

In this Letter, we present the first search for *CP* violating decays of the $\Upsilon(4S)$. The data sample used contains 535×10^6 $\Upsilon(4S)$ mesons collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [6]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [7]. Two inner detector configurations were used. A 2.0 cm radius beam pipe and a 3-layer silicon vertex detector were used for the first sample of 152×10^6 $B\bar{B}$ pairs, while a 1.5 cm radius beam pipe, a 4-layer silicon detector, and a small-cell inner drift chamber were used to record the remaining 383×10^6 $B\bar{B}$ pairs [8].

The identity of each charged track is determined by a sequence of likelihood ratios that determine the hypothesis 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 2.68×10^5 Monte Carlo (MC) simulation events for each signal category. For background MC events, we use a sample of 3.9×10^{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 data set used in the present analysis, the MC simulation predicts a small signal yield, 0.04 events, when we choose the combination $(f_1, f_2) = (J/\psi K_S^0, J/\psi K_S^0)$ and fully reconstruct both $J/\psi K_S^0$ final states. Here we use the $J/\psi \to e^+e^-$, $\mu^+\mu^-$, and $K_S^0 \to \pi^+\pi^-$ modes. In order to increase the signal yield, we instead adopt a partial reconstruction method. We fully reconstruct one $B^0 \to J/\psi K_S^0$ decay (called $f_{J/\psi K_S^0}$ hereafter) and find another K_S^0 (called ${}^{\rm tag}K_S^0$ hereafter) from the remaining particles. We then reconstruct the recoil mass ($M^{\rm recoil}$) using $J/\psi K_S^0$ and ${}^{\rm tag}K_S^0$. The recoil mass distribution should in principle include peaks that correspond to the η_c, J/ψ, χ_{c1}, or $\psi(2S)$. We choose two of the possible combinations, $(f_1, f_2) = (f_{J/\psi K_S^0}, J/\psi {}^{\rm tag}K_S^0)$ and $(f_{J/\psi K_S^0}, \eta_c {}^{\rm tag}K_S^0)$. In the following, these are referred to as inclusive-J/ψ combinations and inclusive-η_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 $J/\psi \to e^+e^-$, $\mu^+\mu^-$ 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 $-0.15~{\rm GeV}/c^2 < M_{ee(\gamma)} - m_{J/\psi} < 0.036~{\rm GeV}/c^2$ and $-0.06~{\rm GeV}/c^2 < M_{\mu\mu} - m_{J/\psi} < 0.036~{\rm GeV}/c^2$, where $m_{J/\psi}$ denotes the nominal mass of J/ψ; $M_{ee(\gamma)}$ 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 $K_S^0 \to \pi^+\pi^-$ decays are oppositely charged track pairs that have an invariant mass within $\pm 0.016~{\rm GeV}/c^2$ ($\simeq 4\sigma$) 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 ${}^{\rm tag}K_S^0$.

For the full reconstruction of a B decay, we use the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where $E_{\rm beam}^{\rm cms}$ is the beam energy in the center-of-mass system (cms) of the $\Upsilon(4S)$ resonance, and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum of the reconstructed B candidate, respectively. The $M_{\rm bc}$ and ΔE distributions are shown in Fig. 1. The signal is extracted from an unbinned extended maximum-likelihood fit to the $M_{\rm bc}$-ΔE 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 $M_{\rm bc}$ (ΔE) distribution. We obtain 8283 ± 94 $f_{J/\psi K_S^0}$ events when we do not require a ${}^{\rm tag}K_S^0$.

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

The dominant source of background is generic B^0 decays. A partially reconstructed B candidate should be flavor nonspecific if it is a signal event. On the other

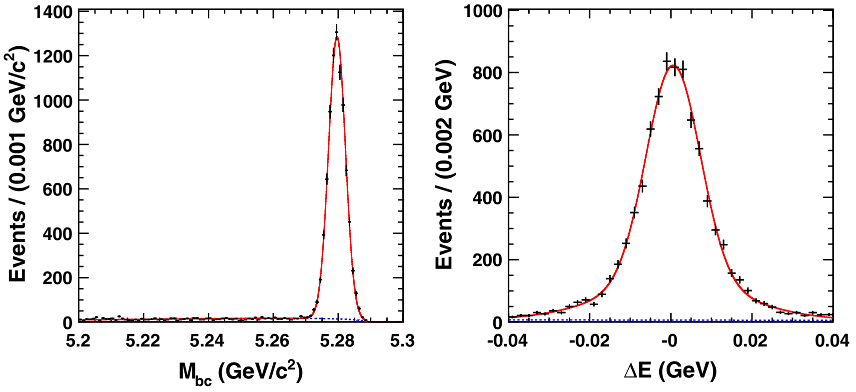

FIG. 1 (color online). $M_{\rm bc}$ (left) and ΔE (right) distributions for $B^0 \to J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$ decay ($l = e, \mu$). The solid curves show the fits to signal plus background distributions, and the dashed curves show the background distributions.

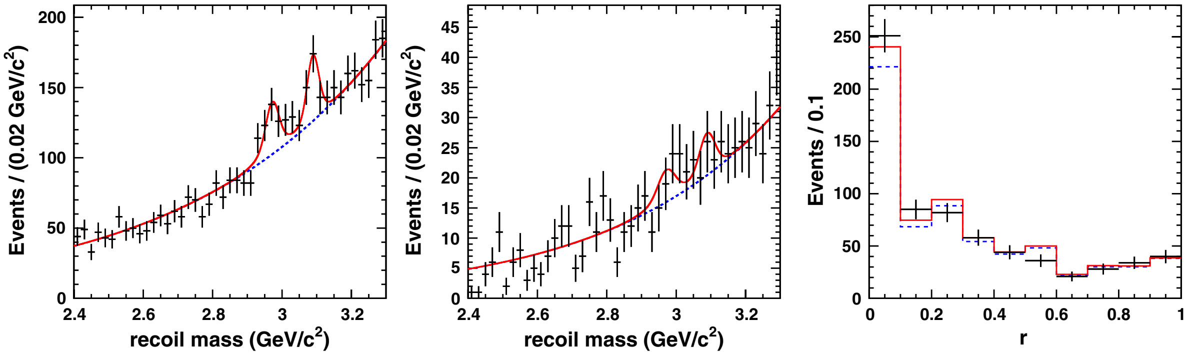

FIG. 2 (color online). Recoil mass distribution for the charged B decay control samples (left), recoil mass (middle), and r (right) distribution for the neutral B decay control samples. The solid curve shows the fit to signal plus background distributions while the dashed curve shows the background distribution.

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

$$\mathcal{L} = \frac{1}{N!}\exp\left(-\sum_k n_k\right)\prod_{i=1}^{N}\left[\sum_k n_k f_k(M_i^{\rm recoil}, r_i)\right], \qquad (3)$$

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/ψ, inclusive-η_c, or background. The parameters $M_i^{\rm recoil}$ and r_i are the recoil mass and r value for the ith 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 $M_{\rm bc}$ sideband data. The PDFs for the r distributions are histograms with 10 bins obtained from MC calculations. The ratio between the inclusive-J/ψ and η_c signals is fixed from the MC calculations.

We check the method using charged B decay control samples, $\Upsilon(4S) \to B^+B^- \to (f_{B^+}, J/\psi^{\rm tag}K^-$ and $\eta_c{}^{\rm tag}K^-)$, where f_{B^+} stands for $J/\psi(e^+e^-, \mu^+\mu^-)K^+$ and $\bar{D}^0(K^+\pi^-, K^+\pi^-\pi^+\pi^-)\pi^+$ decays [11]. Figure 2 shows the recoil mass distribution for the charged B control samples. The fit yields 206 ± 57 signal events, which is in good agreement with the MC expectation (183 events). If we float the ratio between the inclusive-J/ψ and η_c modes, we obtain 96 ± 23 and 109 ± 25 events for the inclusive-J/ψ and η_c modes, respectively. These results are also consistent with the MC expectation, 90 (93) events for inclusive-J/ψ (η_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, $\mathcal{B}[\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K_S^0, (J/\psi, \eta_c)K_S^0]$, are summarized in Table I. 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.

Possible differences between data and the MC calculations in the r distributions are also studied. We use neutral B decay control samples, $\Upsilon(4S) \to B^0\bar{B}^0 \to (f_{B^0}, (J/\psi, \eta_c)^{\rm tag}K_S^0)$ decays, where f_{B^0} represents $B^0 \to D^{(*)-}\pi^+$ and $D^{*-}\rho^+$ followed by the decays $D^{*-} \to \bar{D}^0\pi^-$, $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $D^- \to K^+\pi^-\pi^-$, $\rho^+ \to \pi^+\pi^0$, and $\pi^0 \to \gamma\gamma$. We obtain 35 ± 16 signal events for these samples, which is consistent with the MC prediction (64 events) within 2 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

TABLE I. Systematic uncertainties in the branching fraction measurement.

Source	(%)
Recoil mass distribution	20.5
r distribution	4.2
Reconstruction efficiency	5.7
Number of $B\bar{B}$ pairs	1.3
Branching fractions of subdecays	10.9
Total	24.3

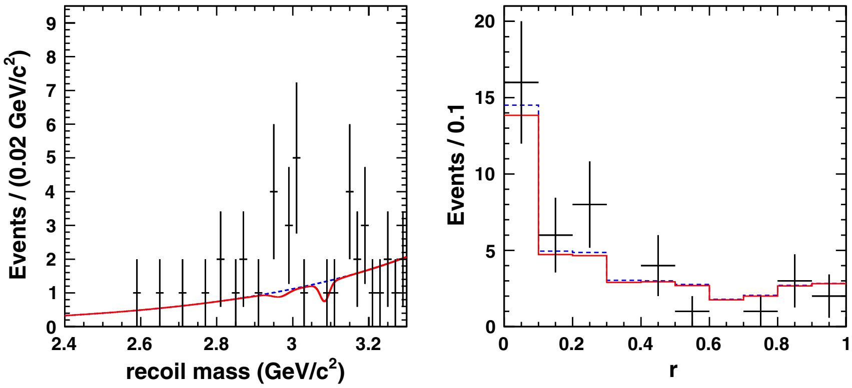

FIG. 3 (color online). Recoil mass (left) and r (right) distribution for samples reconstructed as $\Upsilon(4S) \to [J/\psi K_S^0, (J/\psi, \eta_c)K_S^0]$ decay. The solid lines show the fits to signal plus background distributions while the dashed lines show the background distributions.

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 (2.6%) is included in the systematic error from the r distribution. We also repeat the fit without using the r distribution, which yields a result that differs by 3.3% from the nominal fit result. We assign a 4.2% systematic uncertainty for the r distribution, which is the sum in quadrature of these two errors.

Systematic uncertainties from event reconstruction are studied by varying the particle identification, K_S^0 selection, and other requirements. The resulting changes in the signal yield in data and MC calculations for $B^0 \to J/\psi K_S^0$ and $B^+ \to J/\psi K^+$ are used to estimate the systematic error. In total, 5.7% of the systematic uncertainty that is obtained from the sum in quadrature of differences between data and MC calculations is assigned for event reconstruction. The uncertainty in the total number of $B\bar{B}$ pairs is 1.3%. Uncertainties in the daughter branching fractions [5] are dominated by those for the η_c decays.

The results of the final fit are shown in Fig. 3. 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 [12], where the PDFs are smeared to include systematic uncertainties. We obtain $\mathcal{B}[\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K_S^0, (J/\psi, \eta_c)K_S^0] < 4 \times 10^{-7}$ at the 90% confidence level, where the SM prediction is 1.4×10^{-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 535×10^6 $B\bar{B}$ pairs obtained via decays of the $\Upsilon(4S)$ resonance, no significant signals were observed. We obtain an upper limit of 4×10^{-7} at the 90% confidence level for the branching fraction of the CP violating modes, $\Upsilon(4S) \to B^0\bar{B}^0 \to J/\psi K_S^0 + (J/\psi, \eta_c)K_S^0$. 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 5σ significance.

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