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We report a measurement of the CP-violation parameter sin$2\phi_1$ at the $\Upsilon(5S)$ resonance using a new tagging method, called "B-π tagging." In $\Upsilon(5S)$ decays containing a neutral B meson, a charged B, and a charged pion, the neutral B is reconstructed in the $J/\psi K^0_S$ CP-eigenstate decay channel. The initial flavor of the neutral B meson at the moment of the $\Upsilon(5S)$ decay is opposite to that of the charged B and may thus be inferred from the charge of the pion without reconstructing the charged B. From the asymmetry between B-π^+ and B-π^- tagged $J/\psi K^0_S$ yields, we determine sin$2\phi_1 = 0.57 \pm 0.58$(stat) $\pm$ 0.06(syst). The results are based on 121 fb^{-1} of data recorded by the Belle detector at the KEKB e^+e^- collider.

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In the Standard Model (SM), CP-violation arises from an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. Of the three angles of the unitary triangle, $\phi_1 = \arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ [2] has been the most accessible, using the $B \to (c\bar{c})K^0$ process, because the hadronic uncertainty in this case is negligibly small. CP-violation in the neutral B meson system was clearly observed and ϕ_1 was measured by the Belle [3] and *BABAR* [4] collaborations. These measurements used $B^0\bar{B}^0$ pairs that were produced at the $\Upsilon(4S)$ resonance; the pairs are produced in a state with $C = -1$, where C denotes the eigenvalue of charge conjugation. Since the two B mesons in the C-odd pair state are not allowed to have the same b-flavor, B^0B^0 or $\bar{B}^0\bar{B}^0$, the flavor of one B meson is the opposite of the other B. The other B flavor is identified by combining information from primary and secondary leptons, $K^\pm$, Λ baryons, slow and fast pions [5]. The mixing-induced CP-violation at the Υ(4S) vanishes in the time-integrated rates, and thus a precise measurement of the distance between the decay vertices of the two B mesons is required.

The CP-violation parameter sin$2\phi_1$ can also be measured at the $\Upsilon(5S)$ resonance using a new tagging method which we call "B-π tagging" [6]. In the decay of the $\Upsilon(5S)$ to $\bar{B}^{(*)0}B^{(*)+}\pi^-$ or its charge conjugate, the initial flavor of the neutral B meson is determined from the charge of the pion. In the B-π tagging method, the neutral B is fully reconstructed in a CP-eigenstate, while the charged B is not explicitly reconstructed and identified indirectly through the recoil mass of the neutral B and the charged pion. This method works as well for events containing $B^* \to B\gamma$, where one or more photons are present but not reconstructed. The CP-violation parameter sin$2\phi_1$ can be obtained from the time-integrated asymmetry of $BB\pi^+$ and $BB\pi^-$ tagged events:

$$A_{BB\pi} \equiv \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} = \frac{\mathcal{S}x + \mathcal{A}}{1 + x^2} \quad (1)$$

where $N_{BB\pi^+}$ and $N_{BB\pi^-}$ are the observed number of $B^{(*)0}B^{(*)-}\pi^+$ and $\bar{B}^{(*)0}B^{(*)+}\pi^-$ events in which the neutral B decays to a CP-eigenstate, respectively and $\mathcal{S}$ and $\mathcal{A}$ are the mixing-induced and direct CP-violating parameters, respectively. The mixing parameter $x = (m_H - m_L)/\Gamma$, where $\Gamma = (\Gamma_H + \Gamma_L)/2$, is defined in terms of the masses $m_{H,L}$ and the decay widths $\Gamma_{H,L}$ of the heavy (H) and light (L) neutral B mass eigenstates. The mixing parameter $y = (\Gamma_L - \Gamma_H)/2\Gamma$ is assumed to be zero, as the SM predicts its value to be negligibly small [7] and the observed upper limit is $\mathcal{O}(10^{-2})$ [8]. In the case of $B \to (c\bar{c})K^0_S$, the SM predicts $\mathcal{S} = -\eta_{CP}\sin2\phi_1$ and $\mathcal{A} = 0$ with very small theoretical uncertainty [9], where η_{CP} is the CP-eigenvalue of the final state. Therefore, we can write

$$\sin2\phi_1 = -\eta_{CP}\left(\frac{1+x^2}{x}\right)A_{BB\pi}. \tag{2}$$

There are several notable advantages to the B-π tagging method. First, CP-violation is observed through an asymmetry in event yields; a measurement of the decay time of B mesons is not required, and associated systematic uncertainties are avoided. Moreover, the method is applicable to decay channels such as $B \to \pi^0\pi^0$, in which it is difficult to measure decay vertices. Current analyses at the $\Upsilon(4S)$ resonance constrain only $\mathcal{A}$ for this mode [10]. The analysis using this new tagging method can give a constraint on the combination of the parameters $\mathcal{S}$ and $\mathcal{A}$. In addition, as only one B in the incoherent $B\bar{B}$ pair is reconstructed per event, systematic uncertainties associated with flavor tagging, such as tag-side interference [11], do not arise. Finally, the B-π tagging method can be extended to higher Υ resonance decays. For example, final states such as $\bar{B}_s^{(*)}B^{(*)+}K^-$ can be used to measure CP-violation in the $\bar{B}_s$ system by tagging with a K^-. Although the production cross section is smaller than that at the $\Upsilon(4S)$ resonance, B-π tagging at and above the Υ(5S) is likely to become a powerful technique at upgraded B-factories in the future.

In this Letter, we first measure the time-integrated mixing probability χ_d using the flavor specific modes $B^0 \to J/\psi K^{*0}$ and $D^{*-}\pi^+$ [12] to validate the B-π tagging method. We also measure direct CP-violation in the charged $B^+ \to J/\psi K^+$ mode, where the CP asymmetry is known to be very small [13]. Finally, we report a measurement of $\sin2\phi_1$ using the CP-eigenstate mode $B^0 \to J/\psi K^0_S$ with $\eta_{CP} = -1$.

The results reported here are based on 121 fb^{-1} of data recorded by the Belle detector [14] at the KEKB e^+e^- collider [15], running at the center-of-mass (c.m.) energy of the $\Upsilon(5S)$ resonance. The Belle detector is a general-purpose magnetic spectrometer which consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals. The devices are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K^0_L mesons and to identify muons (KLM).

All charged tracks other than $K^0_S \to \pi^+\pi^-$ daughters are required to originate from the interaction point (IP). Charged kaons and pions are identified by combining information from the energy loss measurement in the CDC, the flight time measured by the TOF, and the response of the ACC [16]. Electrons are identified by a combination of the energy loss measurement in the CDC, the ratio of the cluster energy in the ECL to the track momentum measured by the SVD and CDC, and the shower shape in the ECL. Muons are identified by the track penetration depth and hit scatter in the KLM.

We reconstruct J/ψ mesons in the leptonic channels e^+e^- or $\mu^+\mu^-$. For the $e^\pm$ candidates, we add the four-momentum of every photon detected within 0.05 radians of the original track direction. The invariant mass of e^+e^- pairs is then required to satisfy -100 MeV/c^2 $< M_{e^+(\gamma)e^-(\gamma)}$-$m_{J/\psi} < +30$ MeV/c^2, where $m_{J/\psi}$ is the nominal J/ψ mass; the interval is asymmetric because small residual radiative tails remain. For $\mu^+\mu^-$ pairs, we require the invariant mass to be within 30 MeV/c^2 of the nominal J/ψ mass. The J/ψ mass resolution is about 10 MeV/c^2.

The K^0_S candidates are formed by combining two oppositely charged tracks, assuming both are pions. Since the K^0_S's can be selected with low background, we apply a loose mass selection that requires an invariant mass within 30 MeV/c^2 of the K^0 mass. We then impose the following additional requirements: (1) the two pion tracks must have a large distance of closest approach to the IP in the plane perpendicular to the electron beam line; (2) the pion tracks must intersect at a common vertex that is displaced from the IP; (3) the K^0_S candidate's momentum vector should originate from the IP.

Candidates for K^{*0} and $\bar{D}^0$ mesons are reconstructed in the $K^{*0} \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$ channels, respectively. They are formed by combining oppositely charged kaon and pion tracks and requiring the invariant mass to lie within 50 MeV/c^2($\sim 1\Gamma$) for K^{*0} and within 10 MeV/c^2($\sim 2\sigma$) for $\bar{D}^0$ of the nominal masses, respectively. D^{*-} candidates are reconstructed by combining a $\bar{D}^0$ candidate with a π^-. The mass difference between the D^{*-} and $\bar{D}^0$ candidates is then required to be within 2 MeV/c^2($\sim 3.5\sigma$) of the nominal mass difference.

The B candidates are required to have an invariant mass within 20 MeV/c^2 of the B mass, which corresponds to approximately $\pm2\sigma$, $\pm2.7\sigma$, $\pm2.4\sigma$ and $\pm3\sigma$ intervals for the $D^{*-}\pi^+$, $J/\psi K^{*0}$, $J/\psi K^+$, and $J/\psi K^0_S$ modes, respectively. To select B mesons in $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ events, we require 5.348 GeV/c^2 $< M_{\rm bc} <$ 5.440 GeV/c^2, where $M_{\rm bc}$ is the beam-energy-constrained mass, $M_{\rm bc} = \sqrt{(E^{\rm cms}_{\rm beam})^2 - (p^{\rm cms}_B)^2}$. The quantities $E^{\rm cms}_{\rm beam}$ and $p^{\rm cms}_B$ are the beam energy and momentum of the B candidate in the c.m. frame. If we neglect detector resolution, $M_{\rm bc}$

is less than 5.325 GeV/c^2 in $\Upsilon(5S) \to B^{(*)}B^{(*)}$ events. On the other hand, $M_{\rm bc}$ is higher than 5.351 GeV/c^2 in $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$ events. Even if we consider the effect of detector resolution, we can separate $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$ and $\Upsilon(5S) \to B^{(*)}B^{(*)}$ decays.

To suppress $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum backgrounds, we apply selections on topological variables measured in the c.m. system. The ratio of the second to the zeroth Fox-Wolfram moments [17] is required to be less than 0.5 for the J/ψ final states, $J/\psi K^{*0}$, $J/\psi K^+$ and $J/\psi K^0_S$, for which the background level is low, and less than 0.4 for the $D^{*-}\pi^+$ final state. To further reduce the continuum background for the $D^{*-}\pi^+$ mode, the angle between the thrust axis of the particles forming the B candidate and the thrust axis of all other particles in the event, $\theta^{\rm cms}_{\rm thr}$, is required to satisfy $|\cos\theta^{\rm cms}_{\rm thr}| < 0.75$. These selections retain 98% (78%) of the signal and remove 18% (74%) of the background for the J/ψ ($D^{*-}\pi^+$) final states. More than one B candidate per event is allowed. The probability of multiple candidates, however, is less than 1% per event. The reconstruction efficiencies for the $D^{*-}\pi^+$, $J/\psi K^{*0}$, $J/\psi K^+$, and $J/\psi K^0_S$ modes are 24.6%, 21.2%, 44.4%, and 37.7%, respectively.

We then combine a reconstructed B candidate with each charged pion that was not used in the reconstruction of the B candidate. The point of closest approach for the pion is required to be within 1 cm of the vertex of the reconstructed B decay in the plane perpendicular to the electron beam. Pion tracks identified as $K^0_S \to \pi^+\pi^-$ daughters are rejected. We calculate the missing mass:

$$M^2_{\rm miss} \equiv [P_{\rm total} - (P_B + P_{\pi^\pm})]^2 \tag{3}$$

where $P_{\rm total}$, P_B, and $P_{\pi^\pm}$ are the total 4-momenta of the initial state, the reconstructed B meson candidate, and the pion candidate, respectively. To improve the missing mass resolution, mass- and vertex-constrained fits are applied to B, J/ψ, K^0_S, D^{*+} and D^0 candidates, and a vertex-constrained fit is applied to K^* candidates. The tagging efficiencies for the $B\bar{B}\pi$, $B^*\bar{B}\pi + B\bar{B}^*\pi$, and $B^*\bar{B}^*\pi$ decay channels are 70.6%, 64.7%, and 54.1%, respectively. For the $BB\pi$ channel, the missing mass is equal to the nominal B mass, while for the $B\bar{B}^*\pi$, $B^*\bar{B}\pi$ and $B^*\bar{B}^*\pi$ channels, the missing mass is shifted by approximately the B^*-B mass difference (46 MeV) for each unreconstructed photon from a B^* decay.

The dominant sources of background are random track combinations and initial-state radiation (ISR) processes i.e. $e^+e^- \to \Upsilon(4S)\gamma \to B\bar{B}\gamma$ [18]. The combinatorial background arises mainly from combinations of correctly reconstructed B mesons with pions from the other B. These backgrounds do not peak in the missing mass distribution.

To validate the B-π tagging method, we extract the time-integrated mixing probability, χ_d, from the missing mass distribution in the flavor-specific modes $B \to J/\psi K^{*0}$ and $D^{*-}\pi^+$. For each mode, events are sorted into four categories according to the flavor of the B candidate and the charge of the pion. The B^0-π^+ and $\bar{B}^0$-π^- combinations are unmixed while $\bar{B}^0$-π^+ and B^0-π^- are mixed processes. The value of χ_d is extracted from the yields of mixed and unmixed processes, $N_{\rm mixed}$ and $N_{\rm unmixed}$, respectively:

$$\chi_d = \frac{N_{\rm mixed}}{N_{\rm mixed} + N_{\rm unmixed}}. \tag{4}$$

An extended unbinned maximum likelihood fit in missing mass is simultaneously applied to the $J/\psi K^{*0}$ and $D^{*-}\pi^+$ samples as shown in Ref. [19]. The $B\bar{B}^*\pi + B^*\bar{B}\pi$ and $B^*\bar{B}^*\pi$ signals are modeled by two Gaussians with parameters fixed from Monte Carlo (MC) samples. The ratio of the sum of $B\bar{B}^*\pi$ and $B^*\bar{B}\pi$ to the $B^*\bar{B}^*\pi$ yield is floated. The $B\bar{B}\pi$ and $B\bar{B}\pi\pi$ decay channels are not included in the fit, as their contributions were found to be negligible in other analyses [18]. The $BB\pi$ channel is expected to be suppressed by angular momentum considerations, and the $BB\pi\pi$ channel is expected to be suppressed due to the limited phase space. The combinatorial and ISR backgrounds are described by an ARGUS function [20]. The endpoint of the ARGUS function is fixed from the MC samples. The background yields are floated independently in the fits to the four B-π charge combinations. Assuming there is no direct CP-violation, we obtain $\chi_d = 0.19 \pm 0.09$(stat), which is consistent with the current world average of 0.1864 ± 0.0022 [21]. The $J/\psi K^{*0}$ and $D^{*-}\pi^+$ signal yields are 41.2 ± 9.5 and 29.6 ± 9.0 events, respectively.

We also check direct CP-violation from a charged B mode, $B^+ \to J/\psi K^+$. The missing mass distributions for B^+-π^- and B^--π^+ combinations are fitted with the same signal and background functions as used for the flavor specific modes as shown in Ref. [19]. The signal yield is 64.8±11.9 events. We find $A_{BB\pi} = 0.02 \pm 0.17$, which is

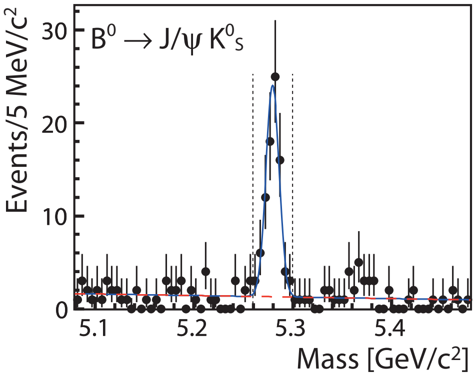

FIG. 1. Invariant mass of reconstructed $B^0 \to J/\psi K^0_S$ candidates. The background component is shown by the dashed curve. The sum of signal and background components is shown by the solid curve. The vertical lines show the requirement on the B^0 mass.

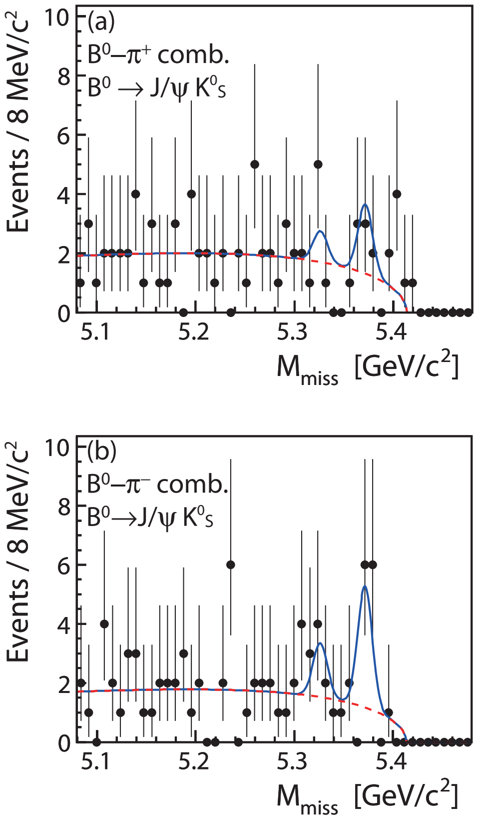

FIG. 2. Missing mass distributions for $B^0 \to J/\psi K_S^0$ candidates tagged by (a) π^+ and (b) π^- in the $\Upsilon(5S)$ data sample. The solid curve is the fit projection for the sum of signal and background. The dashed curve shows the background component. Two peaks correspond to the $B\bar{B}^*\pi + B^*\bar{B}\pi$ (left) and $B^*\bar{B}^*\pi$ (right) decay channels, respectively.

consistent with zero asymmetry, as expected. These two measurements validate the B-π tagging method within the available statistics.

The sin$2\phi_1$ parameter is extracted from the CP-eigenstate mode, $B^0 \to J/\psi K_S^0$. The B meson yield is 75.9 ± 9.5 events as determined from a fit to the reconstructed B mass distribution as shown in Fig. 1. The signal and background are fitted with a Gaussian and a first-order Chebyshev polynomial, respectively. We then fit the π^+ and π^- tagged samples in the missing mass distributions with the same signal and background functions as used for the flavor specific and charged modes. The result is shown in Fig. 2. Two peaks correspond to the $B\bar{B}^*\pi + B^*\bar{B}\pi$ and $B^*\bar{B}^*\pi$ decay channels, respectively. We obtain $A_{BB\pi} = 0.28 \pm 0.28(\text{stat})$. The signal yields tagged by π^+ and π^- mesons are 7.8 ± 3.9 and 13.7 ± 5.3 events, respectively. Figure 3 shows the resulting two-dimensional confidence regions in the $\mathcal{S}$ and $\mathcal{A}$ plane from Eq. (1), taking the mixing parameter x to be 0.771 ± 0.007 [21]. Assuming $\mathcal{A} = 0$, we obtain

$$\sin 2\phi_1 = 0.57 \pm 0.58(\text{stat}) \pm 0.06(\text{syst}). \tag{5}$$

The dominant systematic uncertainty for sin$2\phi_1$ arises from the signal and background shape parameters fixed with MC samples. This uncertainty is evaluated by varying the fitted parameters, the means and width of the two Gaussians for the signal and the endpoint of the ARGUS function, by the difference observed between the data and MC samples for $B \to J/\psi K^{*0}$ and $D^{*-}\pi^+$ and found to be 0.055. The systematic uncertainty from possible $B\bar{B}\pi$ and $B\bar{B}\pi\pi$ contributions is estimated to be 0.005 by refitting the data using a fitting function that includes $BB\pi$ and $BB\pi\pi$. The ratios of $B\bar{B}\pi$ and $B\bar{B}\pi\pi$ to the sum of $B\bar{B}^*\pi$ and $B^*\bar{B}\pi$ are set to the upper limits determined in the $B \to J/\psi K^{*0}$ and $D^{*-}\pi^+$ modes. The systematic uncertainty from a possible pion reconstruction asymmetry is evaluated to be 0.015 using the following equation:

$$\frac{\epsilon^{\pi^+}}{\epsilon^{\pi^-}} = \frac{N_{D^{*+}}/N_{D^0}}{N_{D^{*-}}/N_{\bar{D}^0}} \tag{6}$$

where $\epsilon^{\pi^\pm}$ is the detection efficiency of $\pi^\pm$ and $N_{D^{*+}}$ (N_{D^0}) is the total number of reconstructed D^{*+} (D^0) mesons in the $\Upsilon(4S)$ data sample. The D^{*+} is reconstructed from $D^0\pi^+$, and D^0 is reconstructed from $K^-\pi^+$. We require pions from D^{*+} to be in the kinematic region accessible to pions from $\Upsilon(5S)$ decays. Since the detection efficiencies for kaons and pions from D^0 cancel, the detection efficiency for pions from the D^{*+} decay can be evaluated. The ratio $\epsilon^{\pi^+}/\epsilon^{\pi^-}$ is estimated to be 1.009 ± 0.007, and 1.016 is used for the calculation of the systematic uncertainty. The systematic uncertainties from the mixing parameters x and y [8, 21] are estimated to be 0.001 and 0.012, respectively. The total systematic uncertainty is estimated by summing the above uncertainties in quadrature and found to be 0.058.

In conclusion, we report a measurement of sin$2\phi_1$ with a new tagging method called B-π tagging, using a 121 fb^{-1} data sample collected at the $\Upsilon(5S)$ resonance. This method is complementary to time-dependent analyses using flavor tagging methods at the $\Upsilon(4S)$ resonance [3, 4]. We measure sin$2\phi_1$ to be $0.57 \pm 0.58(\text{stat}) \pm 0.06(\text{syst})$, which is consistent with the value obtained on the $\Upsilon(4S)$ resonance. The B-π tagging method allows the measurement of CP-violation without decay time information and thus has great potential for the $B \to \pi^0\pi^0$ and $\bar{B}_s^{(*)}B^{(*)+}K^-$ decay channels at future high luminosity B-factory experiments.

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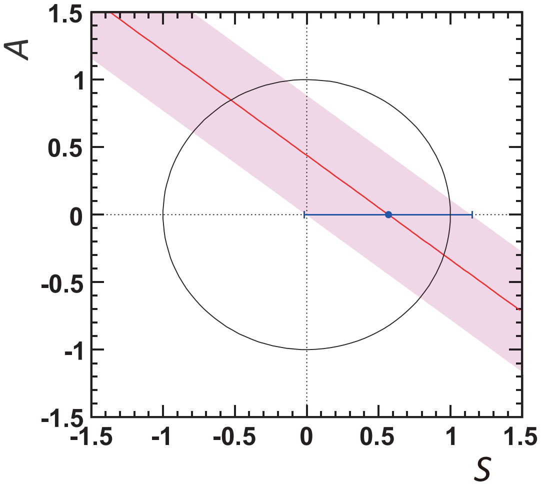

FIG. 3. Confidence region for $\mathcal{S}$ and $\mathcal{A}$. The circle shows the physical boundary. The shaded region shows the $\pm 1\sigma$ region using the B-π tagging method at the $\Upsilon(5S)$ resonance and the point with an error bar is the $\mathcal{S} = \sin 2\phi_1$ measurement assuming no direct CP violation ($\mathcal{A} = 0$).

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