IMPROVED MEASUREMENT OF CP ASYMMETRY IN THE NEUTRAL B MESON SYSTEM

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We present an improved measurement of the standard model CP violation parameter \( \sin 2\phi_1 \) (also known as \( \sin 2\beta \)) based on a sample of \( 45 \times 10^6 \) \( B\bar{B} \) pairs collected at the \( \Upsilon(4S) \) resonance with the Belle detector at the KEKB asymmetric-energy \( e^+ e^- \) collider. One neutral \( B \) meson is reconstructed in the \( J/\psi K^0_S, \psi(2S)K^0_S, \chi_c K^0_S, J/\psi K^0_L \) \( CP \)-eigenstate decay channel and the flavor of accompanying \( B \) meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two \( B \) meson decay points, we obtain \( \sin 2\phi_1 = 0.82 \pm 0.12 \) (stat) \( \pm 0.05 \) (syst). The result is preliminary.

In the Standard Model (SM), \( CP \) violation arises from an irreducible complex phase in the weak interaction quark mixing matrix (CKM matrix). In particular, the SM predicts a \( CP \) violating asymmetry in the time-dependent rates for \( B^0 \) and \( \bar{B}^0 \) decays to a common \( CP \) eigenstate, \( f_{CP} \), with negligible corrections from strong interactions:

\[
A(t) \equiv \frac{\Gamma(B^0 \to f_{CP}) - \Gamma(\bar{B}^0 \to f_{CP})}{\Gamma(B^0 \to f_{CP}) + \Gamma(\bar{B}^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d t, \tag{1}
\]

where \( \Gamma(B^0, \bar{B}^0 \to f_{CP}) \) is the decay rate for a \( B^0 \) or \( \bar{B}^0 \) to \( f_{CP} \) dominated by \( b \to c \bar{s} s \) transition at a proper time \( t \) after production, \( \xi_f \) is the \( CP \) eigenvalue of \( f_{CP} \), \( \Delta m_d \) is the mass difference between the two \( B^0 \) mass eigenstates, and \( \phi_1 \) is one of the three interior angles of the CKM unitarity triangle, defined as \( \phi_1 \equiv \pi - \arg(-V^*_{tb}V_{td}/-V^*_{tb}V_{cd}) \).

In this paper, we report an improved measurement of \( \sin 2\phi_1 \) using \( 45 \times 10^6 \) \( B\bar{B} \) pairs (42 fb\(^{-1}\)) collected with the Belle detector at the \( \Upsilon(4S) \) resonance in collisions of 8.0 GeV \( e^+ e^- \)

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to 3.5 GeV $e^+$ at KEKB, where two $B$ mesons reside in a coherent $p$-wave state until one of them decays. The decay of one of the $B$ mesons to a self-tagging state, $f_{\text{tag}}$, i.e., a final state that distinguishes $B^0$ and $B^0$, at a time $t_{\text{tag}}$ projects the accompanying meson onto the opposite $b$-flavor at that time; this meson decays to $f_{\text{CP}}$ at time $t_{\text{CP}}$. The $CP$ violation manifests itself as an asymmetry $A(t)$, where $t$ is the proper time interval $t \equiv t_{\text{CP}} - t_{\text{tag}}$. At KEKB, the $Y(4S)$ resonance is produced with a boost of $\beta \gamma = 0.425$ along the electron beam direction (z direction). Because the $B^0$ and $\bar{B}^0$ mesons are nearly at rest in the $Y(4S)$ center of mass system ( cms), $\Delta t$ can be determined as $\Delta t \simeq z/(\beta \gamma)c$, where $z$ is the $z$ distance between the $f_{\text{CP}}$ and $f_{\text{tag}}$ decay vertices, $z \equiv z_{\text{CP}} - z_{\text{tag}}$. The average value for $z$ is approximately 200 $\mu$m.

We reconstruct $B^0$ decays to the following $CP$ eigenstates: $J/\psi K^0$, $\psi(2S) K^0$, $\chi_{c1} K^0$, $\eta K^0$ for $\xi_f = -1$ and $J/\psi K^0_L$ for $\xi_f = +1$. We also use $B^0 \rightarrow J/\psi K^{*0}$ decays where $K^{*0} \rightarrow K^0 \pi^0$. Here the final state is a mixture of even and odd $CP$, depending on the relative orbital angular momentum of the $J/\psi$ and $K^{*0}$. We find that the final state is primarily $\xi_f$: the $\xi_f = -1$ fraction is $0.19 \pm 0.04$ (stat) $\pm 0.04$ (syst).

For reconstructed $B$ candidates except $J/\psi K^0$, we identify $B$ decays using the energy difference $\Delta E \equiv E_{\text{cms}}^B - E_{\text{beam}}$, the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^B)^2 - (p_{B}^T)^2}$, where $E_{\text{beam}}^B$, $E_{\text{cms}}^B$, and $p_{B}^T$ are the beam energy, the energy, and the momentum of the reconstructed $B$ candidate in the cms, respectively. Figure I (top) shows the $M_{\text{bc}}$ distributions for all $B^0$ candidates except for $B^0 \rightarrow J/\psi K^0$ that are found in the signal region. Table 1 lists the numbers of observed candidates ($N_{\text{ev}}$) and the background ($N_{\text{bkg}}$) estimated by extrapolating the rate in the non-signal $\Delta E$ vs $M_{\text{bc}}$ region into the signal region. Candidate $B^0 \rightarrow J/\psi K^0$ decays are selected by requiring electromagnetic calorimeter (ECL) and/or $K^0_L$ and muon detector (KLM) hit patterns that are consistent with the presence of a shower induced by a neutral hadron. The centroid of the shower is required to be in a 45 degree cone centered on the $K^0_L$ direction that is inferred from two-body decay kinematics and the measured four-momentum of the $J/\psi$. Figure II (bottom) shows the $p_{B}^T$ distribution, calculated with the $B^0 \rightarrow J/\psi K^0_L$ two-body decay hypothesis. The histograms are the results of a fit to the signal and background distributions. There are 767 entries in total in the region $0.20 < p_{B}^T \leq 0.40$ GeV/c with KLM clusters and in $0.20 < p_{B}^T \leq 0.40$ GeV/c with clusters in the ECL only. The fit finds a signal purity of 60%. The reconstruction and selection criteria for used channels are described elsewhere.

Leptons, charged pions, kaons, and $\Lambda$ baryons that are not associated with a reconstructed $CP$ eigenstate decay are used to identify the $b$-flavor of the accompanying $B$ meson; high mo-

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Table 1: The numbers of observed candidates ($N_{\text{ev}}$) and the estimated background ($N_{\text{bkg}}$) in the signal region for each $f_{\text{CP}}$ mode.

| Mode                        | $N_{\text{ev}}$ | $N_{\text{bkg}}$ |
|-----------------------------|-----------------|------------------|
| $J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)$ | 636             | 31.2             |
| $J/\psi(\ell^+\ell^-)K^0_S(\pi^0\pi^-)$ | 102             | 20.8             |
| $\psi(2S)(\ell^+\ell^-)K^0_S(\pi^+\pi^-)$ | 49              | 2.4              |
| $\psi(2S)(J/\psi\pi^+\pi^-)K^0_S(\pi^+\pi^-)$ | 57              | 4.3              |
| $\chi_{c1}(J/\psi\gamma)K^0_S(\pi^+\pi^-)$ | 34              | 2.3              |
| $\eta(0)(K^+\pi^-)K^0_S(\pi^+\pi^-)$ | 39              | 11.1             |
| $\eta(0)(K^0\pi^-)K^0_S(\pi^+\pi^-)$ | 33              | 8.9              |
| $J/\psi(\ell^+\ell^-)K^0_L$ | 55              | 6.0              |
| $J/\psi(\ell^+\ell^-)K^0_L$ | 767             | 307              |
momentum leptons from $b \to c\ell^−τ$, lower momentum leptons from $c \to s\ell^−τ$, charged kaons and Λ baryons from $b \to c \to s$, fast pions from $B^0 \to D^{(*)−}(π^+, ρ^+, a_1^+, \text{etc.})$, and slow pions from $D^{*-} \to \bar{D}^0π^-$. Using those tracks, two parameters, $q$ and $r$, are assigned to an event. The first, $q$, has the discrete values $q = ±1$ that is $+1(-1)$ when $B_{\text{tag}}$ is likely to be a $B^0(\bar{B}^0)$, and the parameter $r$ is an event-by-event flavor-tagging dilution factor ranging from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six intervals of $r$, according to flavor purity; the wrong-tag probabilities, $w_l$ ($l = 1, 6$), for the final fit are determined directly from data. The decay to exclusively reconstructed self-tagged channels are utilized to obtain $w_l$ using time-dependent $B^0-\bar{B}^0$ mixing oscillation: $(N_{OF} - N_{SF})/(N_{OF} + N_{SF}) = (1 - 2w_l)\cos(Δm_dΔt)$. Here $N_{OF}$ and $N_{SF}$ are the numbers of opposite and same flavor events. The total effective tagging efficiency is $\sum_{l=1}^{6}f_l(1 - 2w_l)^2 = 0.270 ± 0.008(\text{stat})^{+0.006}_{-0.009}(\text{syst})$, where $f_l$ is the event fraction for each $r$ interval.

The vertex position for $f_{CP}$ is reconstructed using leptons from $J/ψ$ decay and that for $f_{tag}$ is obtained with well reconstructed tracks not assigned to $f_{CP}$. Tracks that form a $K^0_S$ invariant mass are not used. Each vertex position is required to be consistent with the interaction point profile smeared in the $r-φ$ plane by the $B$ meson decay length. The requirement enables us to determine a vertex even with a single track. The fraction of such vertices is about 10% for $z_{CP}$ and 30% for $z_{tag}$. A proper-time interval resolution, $R_{\text{tag}}(Δt)$, consists of a convolution of four components: detector resolution for $z_{CP}$ and $z_{tag}$, shift in the $z_{tag}$ reconstruction due to secondary tracks originated from charged hadrons such as $D^+$ and $D^0$, and smearing effect due to kinematic approximation in converting $Δz$ to $Δt$. We find broad outlier components in $Δz$ distributions due to mis-reconstruction, which are represented by Gaussian distributions. We simultaneously determine ten resolution parameters from data with a fit of neutral and charged $B$ meson lifetime and obtain a $Δt$ resolution of $\sim 1.56$ ps (rms). The width and the fraction of the outlier component are determined to be $36^{+5}_{-4}$ ps, and $(0.06^{+0.03}_{-0.02})%$ or $(3.1 ± 0.4)%$ (multiple- or single-track case).

After vertexing we find 766 events with $q = +1$ flavor tags and 784 events with $q = −1$. Figure 2 shows the observed $Δt$ distributions for the $qξ_f = +1$ (solid points) and $qξ_f = −1$ (open points) event samples. The asymmetry between two distributions demonstrates the violation of the $CP$ symmetry. We determine sin $2ϕ_1$ from an unbinned maximum-likelihood fit to the observed $Δt$ distributions. The probability density function (pdf) expected for the signal distribution is given by

$$P_{\text{sig}}(Δt, q, w_l, ξ_f) = \frac{e^{-|Δt|/τ_{B^0}}}{2τ_{B^0}}[1 - qξ_f(1 - 2w_l)\sin 2ϕ_1 \sin Δm_dΔt],$$

where we fix the $B^0$ lifetime and mass difference at their world average values. Each pdf is

![Figure 2: $Δt$ distributions for the events with $qξ_f = +1$ (solid points) and $qξ_f = −1$ (open points). The results of the global fit with sin $2ϕ_1 = 0.82$ are shown as solid and dashed curves, respectively.](image-url)
where the product is over all events. The preliminary result of the fit is
\[ m = \text{value}. \]
The errors introduced by uncertainties in \( \Delta \) distribution (\( \pm \phi \)) is the signal probability calculated as a function of \( \Delta t \) for \( J/\psi K^0_L \) and of \( \Delta E \) and \( M_{bc} \) for other modes. \( \mathcal{P}_{bkg}(\Delta t) \) is a pdf for combinatorial background events that is modeled as a sum of exponential and prompt components. It is convolved with a sum of two Gaussians, \( R_{bkg} \), \( P_{ol} \) and \( f_{ol} \) are the pdf and the fraction for the outlier component. The only free parameter in the final fit is \( \sin 2\phi_1 \), which is determined by maximizing the likelihood function \( L = \prod_i P_i \), where the product is over all events. The preliminary result of the fit is
\[ \sin 2\phi_1 = 0.82 \pm 0.12(\text{stat}) \pm 0.05(\text{syst}). \]

The systematic error is dominated by uncertainties due to effects of the tails of the vertex distribution (\( \pm 0.030 \)). Other significant contributions come from uncertainties (a) in \( w_l \) (\( \pm 0.024 \)), (b) in the resolution function parameters (\( \pm 0.022 \)); (c) in the \( J/\psi K^0_L \) background fraction (\( \pm 0.014 \)). The errors introduced by uncertainties in \( \Delta m_d \) and \( \tau_{B^0} \) are 0.01 or less.

A number of checks on the measurement are performed. Table 2 lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. The result is unchanged if we use the \( w_l \)'s determined separately for \( f_{tag} = B^0 \) and \( B^0 \). A fit to the non-\( CP \) eigenstate self-tagged modes \( B^0 \to D^{(*)-}\pi^+ \), \( D^{*-}\rho^+ \), and \( J/\psi K^*0(K^+\pi^-) \), where no asymmetry is expected, yields \( 0.05 \pm 0.04 \).

We also measure \( CP \) violating asymmetry in \( B^0 \to \eta' K^0_S \) decays based on \( 45 \times 10^6 \) \( B\overline{B} \) pairs. Numbers of fully reconstructed events for \( \eta(\gamma\gamma)\pi\pi K^0_S \) and for \( \rho\gamma K^0_S \) are \( 27.7^{+6.2}_{-5.5} \) and \( 45.4^{+8.6}_{-7.9} \), respectively. Flavor of the accompanying \( B \) meson is identified from its decay products. The decay rate has a time dependence given by
\[ \mathcal{P}_{\eta}(\Delta t, q, w_l) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q(1 - 2w_l)[S\sin(\Delta m_d\Delta t) + C\cos(\Delta m_d\Delta t)] \right\}. \]

From the asymmetry in the \( \Delta t \) distribution, we obtain \( S = 0.27^{+0.54}_{-0.55}(\text{stat}) \pm 0.07(\text{syst}) \) and \( C = 0.12 \pm 0.32(\text{stat}) \pm 0.07(\text{syst}) \).

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