Recent results on the $B CP$-violation parameter $\sin 2\phi_1$, the $B^0_d$-$\overline{B}^0_d$ mixing parameter $\Delta m_d$ and $B$-meson lifetimes are reported. The results are based on 10.5 $fb^{-1}$ of data collected with the Belle detector at KEKB. Using both semileptonic and hadronic decay modes the neutral and charged $B$-meson lifetimes are measured to be $\tau(B^0_d) = 1.548 \pm 0.035$ (stat.) ps and $\tau(B^+) = 1.656 \pm 0.038$ (stat.) ps. The oscillation frequency $\Delta m_d$ for $B^0_d$-$\overline{B}^0_d$ mixing is measured to be $0.522 \pm 0.026$ (stat.) ps$^{-1}$ using semileptonic modes and $0.527 \pm 0.032$ (stat.) ps$^{-1}$ using hadronic modes. The above results are preliminary. The time evolution of $B^0_d$ decays into $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_cK^0_L$, $J/\psi K^0_d$, $J/\psi\pi^0$ modes are studied to obtain $\sin 2\phi_1$. Using 282 fully reconstructed events, $\sin 2\phi_1$ is measured to be

$$\sin 2\phi_1 = 0.58^{+0.32}_{-0.34} \text{ (stat.)} \pm 0.09 \text{ (syst.)}.$$
CP violation is one possible ingredient to understanding the antimatier deficit in the universe. In the Kobayashi-Maskawa theory[2] CP violation is due to the complex phase of the quark mixing matrix. According to this framework, a large asymmetry, $O(1)$ can be expected in $B$ decays. However, the mechanism of the CP violation has not yet been confirmed experimentally. It is crucial to establish the CP violation in $B$ decays expected from the KM theory.

$B_d^0 \to J/\psi K_S^0$ is the most promising decay mode for observing CP violation in $B$ decays because of its low experimental backgrounds and negligible theoretical uncertainties. In the decays into $CP$ eigenstates ($f_{CP}$), $CP$ violation occurs through interference of two decay amplitudes, $A_f e^{-i\gamma/2} e^{-iM t/2} \cos(\Delta m d t)$ for $B_d^0 \to f_{CP}$ and $\tilde{A}_f e^{-i\gamma/2} e^{-iM t/2} i \sin(\Delta m d t)$ for $B_d^0 \to \tilde{B}_d^0 \to f_{CP}$, where $\Gamma$ is the total $B_d^0$ decay width, $\Delta m d$ the mass difference between the two $B_d^0$ mass eigenstates, $A_f = \langle f_{CP}|\mathcal{H}|B_d^0\rangle$ and $\tilde{A}_f = \langle f_{CP}|\mathcal{H}|\tilde{B}_d^0\rangle$. Assuming negligible CP violation in state mixing ($|q/p| \approx 1$) and direct CP violation ($|A_f/\tilde{A}_f| \approx 1$), the decay rates for $B_d^0 \to f_{CP}$ and and its charge conjugate mode $\tilde{B}_d^0 \to f_{CP}$ can be expressed as

$$\Gamma_{B_d^0 \to f_{CP}}(t) \approx A_f^2 e^{-\Gamma t} \{1 - \Im(\lambda) \sin(\Delta m d t)\} = A_f^2 e^{-\Gamma t} \{1 + \xi_f \sin 2\phi_1 \sin(\Delta m d t)\},$$

$$\Gamma_{\tilde{B}_d^0 \to f_{CP}}(t) \approx \tilde{A}_f^2 e^{-\Gamma t} \{1 - \Im(\lambda) \sin(\Delta m d t)\} = \tilde{A}_f^2 e^{-\Gamma t} \{1 - \xi_f \sin 2\phi_1 \sin(\Delta m d t)\}. \quad (1)$$

where $\lambda \equiv q/p \cdot A_f/\tilde{A}_f$, $\xi_f$ is the CP eigenvalue of the $f_{CP}$ state, and $\phi_1$ is defined as $\phi_1 \equiv \pi - \arg \left(\frac{V_{td}^* V_{cb}}{V_{td}^* V_{cb}}\right)$ $B_d^0 \tilde{B}_d^0$ mixing gives $q/p \propto (V_{td}^* V_{cb})/(V_{td}^* V_{cb}^*)$. When $f_{CP}$ is $(\pi)K^0$ ($K^0 \to K^0_S$ or $K^0_L$), $A_f/\tilde{A}_f = \xi_f (V_{tb}^* V_{cd}/V_{tb} V_{cd}^*) \cdot (V_{cb} V_{cd}/V_{cb}^* V_{cd}) = \xi_f (V_{tb}^* V_{cd}/V_{cb} V_{cd})$.

In an asymmetric B factory, $B_d^0 \tilde{B}_d^0$ pairs are produced at the $\Upsilon(4S)$ resonance. The two mesons remain in a coherent $p$-state until one of them decays. The decay of one of the $B$ mesons into a flavor specific final state at time $t_{tag}$ projects the accompanying meson onto the opposite $b$-flavor at that time; this meson decays to $f_{CP}$ at time $t_{CP}$. The decay rates are now functions of $\Delta t \equiv t_{CP} - t_{tag}$ as

$$\Gamma_{B_d^0 \tilde{B}_d^0 \to f_{CP}}(\Delta t) = A_f^2 e^{-\Gamma \Delta t} \{1 \pm \xi_f \sin 2\phi_1 \sin(\Delta m d \Delta t)\}. \quad (2)$$

Since $\Delta t$ is a signed value and integrated rates do not have any asymmetry between $B_d^0$ and $\tilde{B}_d^0$ mesons, time dependent decay rates have to be measured to obtain $\sin 2\phi_1$.

At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta \gamma = 0.425$ along the electron beam direction ($z$ direction). Since the $B_d^0$ and $\tilde{B}_d^0$ mesons are nearly at rest in the $\Upsilon(4S)$ center of mass system (cms), $\Delta t$ can be determined from the $z$ distance between the $f_{CP}$ and $f_{tag}$ decay vertices, $\Delta z \equiv z_{CP} - z_{tag}$, as $\Delta t \simeq \Delta z/\beta \gamma c$. Precise measurement of the $B$ decay positions and proper identification of the flavor of the accompanying $B$ meson are crucial for the measurement of $\sin 2\phi_1$. In this paper, a determination of $\sin 2\phi_1$ is presented along with measurements of the $B_d^0 \tilde{B}_d^0$ mixing parameter $\Delta m d$ and $B$-meson lifetimes. The data sample corresponds to an integrated luminosity of 10.5 $fb^{-1}$ collected with the Belle detector[3] at the KEKB asymmetric $e^+e^-$ (3.5 on 8 GeV) collider[4].

The $B_d^0$ decay modes $B_d^0 \to J/\psi K_S^0$, $\psi(2S)K^0_S$, $\chi_{c1} K^0_S$, $\eta_b K^0_S$, $J/\psi K^0_L$ and $J/\psi \pi^0$ are reconstructed for the $\sin 2\phi_1$ measurement. Fully reconstructed $B$ candidates are selected using the energy difference $\Delta E \equiv E_{B_{\text{cms}}}^\text{cms} - E_{\text{beam}}^\text{beam}$ and the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}}^\text{cms})^2 - (p_{B_{\text{cms}}}^\text{cms})^2}$, where $E_{\text{beam}}^\text{cms}$ is the cms beam energy, and $E_{B_{\text{cms}}}^\text{cms}$ and $p_{B_{\text{cms}}}^\text{cms}$ are the cms energy and momentum of the $B$ candidate. $p_{B_{\text{ cms}}}^\text{cms}$ is employed to select $J/\psi K^0_L$ events where $p_{B_{\text{ cms}}}^\text{cms}$ is calculated by a 0C fit using the $J/\psi$ momentum and the $K^0_L$ direction. We reduce the background by means of a likelihood quantity that combines the $J/\psi$ cms momentum, the angle between the $K^0_L$ and its nearest-neighbor charged track, the charged track multiplicity, and the kinematics
that obtain when the event is reconstructed assuming a $B^+ \rightarrow J/\psi K^{*+}$, $K^{*+} \rightarrow K_L^0 \pi^+$ hypothesis. Fig. 3 shows (a) the $M_{bc}$ distribution for all $f_{CP}$ decay modes combined (other than $B_d^0 \rightarrow J/\psi K_L^0$) and (b) the $p_{B_{CP}}$ distribution for $B_d^0 \rightarrow J/\psi K_L^0$ candidates with the results of the fit. We find 194 events and 131 events with expected backgrounds of 11 events and 54 events for all $f_{CP}$ modes without $K_L^0$ and $J/\psi K_L^0$ modes, respectively.

The flavor of the accompanying $B$ meson is identified using tracks such as; high momentum leptons from $b \rightarrow c \ell^- \nu$, lower momentum leptons from $c \rightarrow s \ell^+ \nu$, charged kaons from $b \rightarrow c \rightarrow s$, high momentum pions from decays of the type $B_d^0 \rightarrow D^{(*)}-(\pi^+, \rho^+, a_1^+, \text{etc.})$, and slow pions from $D^{**} \rightarrow D^0 \pi^-$. We calculate a value $Q_{track} = \{\mathcal{L}(B_d^0) - \mathcal{L}(B_d^0)\}/\{\mathcal{L}(B_d^0) + \mathcal{L}(B_d^0)\}$ in three track categories ($Q_\ell$ for lepton, $Q_K$ for kaon and $Q_\pi$ for pion) for tracks that are not associated with $f_{CP}$, where $\mathcal{L}$ is a likelihood based variables such as the particle identification information and the track momentum. The best $Q$ values from these track categories are combined into one $Q$ value for each event using a three dimensional binned function $Q_{event} = f(Q_{\ell}, Q_K, Q_\pi)$ derived from a large statistics MC sample to take into account correlations between track categories. In an ideal case, $|Q|$ should be related to the probabilities for an incorrect flavor assignment $w$, as $|Q| = 1 - 2w$. The $w$ values are measured using $B_d^0 \rightarrow D^{*-} \ell^+ \nu$, $D^{(*)}-(\pi^+, \rho^+)$ modes. The $b$-flavor of the accompanying $B$ meson is assigned according to the above-described flavor-tagging algorithm, and values of $w$ are determined for six $|Q|$ intervals from the amplitudes of the time-dependent $B_d^0-B_d^0$ mixing oscillations. We obtain $w_1 = 0.470^{+0.031}_{-0.035} (0 < |Q| < 0.25)$, $w_2 = 0.336^{+0.032}_{-0.033} (0.25 < |Q| < 0.5)$, $w_3 = 0.286^{+0.035}_{-0.033} (0.5 < |Q| < 0.625)$, $w_4 = 0.210^{+0.033}_{-0.031} (0.625 < |Q| < 0.75)$, $w_5 = 0.098^{+0.028}_{-0.026} (0.75 < |Q| \leq 0.875)$, $w_6 = 0.020^{+0.023}_{-0.019} (0.875 < |Q| < 1)$. The total effective tagging efficiency is $\sum_i f_i(1-2w_i)^2 = 0.270^{+0.023}_{-0.022}$, where $f_i$ is the fraction of events in each $|Q|$ interval and the error includes both statistical and systematic uncertainties, in good agreement with the MC result of 0.274. We check for a possible bias in the flavor tagging by measuring the effective tagging efficiency for $B_d^0$ and $B_d^0$ self-tagged samples separately, and for different $\Delta t$ intervals. We find no statistically significant difference.

The vertex positions for the $f_{CP}$ and $f_{tag}$ decays are reconstructed using tracks that have at least one 3-dimensional coordinate determined from associated $r\phi$ and $z$ hits in the same SVD layer plus one or more additional $z$ hits in other SVD layers. An interaction point constraint is applied to the vertex fit for both $B$ mesons in order to improve the vertex resolution. The average resolution estimated from data is 88 $\mu$m for $z_{CP}$ and 164 $\mu$m for $z_{tag}$.

We determine $\sin 2\phi_1$ from an unbinned maximum-likelihood fit to the observed $\Delta t$ distributions. The likelihood function is defined as

$$
\mathcal{L}(\sin 2\phi_1) = \prod_i \int_{-\infty}^{\infty} d(\Delta t') \left\{ p_{SIG}^i(\Delta t') R_{SIG}^i(\Delta t_i - \Delta t') + p_{BG}^i(\Delta t') R_{BG}^i(\Delta t_i - \Delta t') \right\},
$$

Figure 1: (a) The beam-constrained mass distribution for all $f_{CP}$ decay modes combined (other than $B_d^0 \rightarrow J/\psi K_L^0$). The shaded area is the estimated background. The dashed lines indicate the signal region. (b) The $p_{B_{CP}}$ distribution for $B_d^0 \rightarrow J/\psi K_L^0$ candidates with the results of the fit. The solid line is the signal plus background; the shaded area is background only. The dashed lines indicate the signal region.
Figure 2: The asymmetry obtained from separate fits to each $\Delta t$ bin; the curve is the result of the global fit ($\sin 2\phi_1 = 0.58$).

$$p_{SIG}^i(\Delta t') = \frac{f_{SIG}^i}{2 \tau(B_d^0)} e^{-|\Delta t'|/\tau_B} \{1 - q \xi_f (1 - 2w_l) \sin 2\phi_1 \sin(\Delta m_d \Delta t')\},$$

$$p_{BG}^i(\Delta t') = \sum_k f_k^i \{(1 - f_{\lambda BG}^k) \cdot \delta(\Delta t') + f_{\lambda BG}^k \frac{\lambda_{BG}}{2} e^{-\lambda_{BG} |\Delta t'|}\},$$

where: $q$ is the sign of the flavor tag variable $Q$; $R_{SIG}^i$ and $R_{BG}^i$ are the resolution functions calculated event-by-event from the track error matrix; $f_{SIG}^i$ and $f_k^i$ are the fractions of the signals and background contributions that are calculated event-by-event using variables such as $\Delta E$, $M_{bc}$ and $p_{cm}^m$; $\lambda_{BG}$, $f_{\lambda BG}^k$ are the background-shape parameters. A description of the $B$ reconstruction, vertex reconstruction, flavor tagging and fit procedure can be found elsewhere.

In the CP analysis, we obtain the result $\sin 2\phi_1 = 0.58_{-0.34}^{+0.32+0.09}$, where the first error is statistical and the second systematic. The systematic errors are dominated by the uncertainties in $w_l$ $(^{+0.05}_{-0.07})$ and the $J/\psi K^0_S$ background $(^{+0.05}_{-0.07})$. Separate fits to the $\xi_f = -1$ and $\xi_f = +1$ event samples give $0.82_{-0.41}^{+0.36}$ and $0.10_{-0.60}^{+0.57}$, respectively. Figure 2 shows the asymmetry obtained by performing the fit to events in $\Delta t$ bins separately, together with a curve that represents $\sin 2\phi_1 \sin(\Delta m_d \Delta t)$ for $\sin 2\phi_1 = 0.58$. We check for a possible fit bias by applying the same fit to non-CP eigenstate modes: $B_d^0 \rightarrow D^{(*)-}\pi^+, D^{*-}\rho^+, J/\psi K^{*0}(K^+\pi^-)$, and $D^{*-}\ell^+\nu$, where “$\sin 2\phi_1$” should be zero, and the charged mode $B^+ \rightarrow J/\psi K^+$. For all the modes combined we find $0.065 \pm 0.075$, consistent with a null asymmetry.

In the $B$ lifetime analysis, $p_{SIG}(\Delta t')$ is replaced by $p_{SIG}(\Delta t') = \frac{f_{SIG}^0}{2 \tau_B} e^{-|\Delta t'|/\tau_B}$. The decay modes $B_d^0 \rightarrow D^{*-}\ell^+\nu$ and $B_d^0 \rightarrow D^{(*)-}(\pi^+, \rho^+)$ are used for the $B_d^0$ lifetime measurements. We obtain $\tau(B_d^0) = 1.517 \pm 0.045$ ps for the semileptonic mode and $\tau(B_d^0) = 1.585_{-0.051}^{+0.053}$ ps for the hadronic modes, where the errors are statistical only. Combining these results, we obtain $\tau(B_d^0) = 1.548_{-0.035}^{+0.035}$ ps. Decay modes $B^+ \rightarrow D^{*0}\ell^+\nu$ and $D^0\pi^+$ are used for the $B^+$ lifetime measurement and give $\tau(B^+) = 1.628 \pm 0.060$ ps and $\tau(B^+) = 1.679_{-0.048}^{+0.049}$ ps, respectively. The combined result is $\tau(B^+) = 1.656 \pm 0.038$ ps. Parameters for the resolution function $R_{SIG}$ are also determined in the lifetime fit and shared by the mixing and CP analysis.

In the mixing analysis, $p_{SIG}(\Delta t')$ is replaced by $p_{SIG}(\Delta t') = \frac{f_{SIG}^0}{4 \tau(B_d^0)} e^{-|\Delta t'|/\tau(B_d^0)} \{1 - (1 - 2w_l) \cos(\Delta m_d \Delta t') \}$ for unmixed $(B_d^0 \overline{B_d^0})$ and mixed $(B_d^0 B_d^0$ and $\overline{B_d^0} \overline{B_d^0})$ events. Using $B_d^0 \rightarrow D^{*-}\ell^+\nu$ and $B_d^0 \rightarrow D^{(*)-}(\pi^+, \rho^+)$ decay modes, we obtain $\Delta m_d = 0.522 \pm 0.026$ ps$^{-1}$ and $\Delta m_d = 0.527 \pm 0.032$ ps$^{-1}$, respectively. Our results for the $B$ lifetime and the $B_d^0-\overline{B_d^0}$ mixing oscillation frequency $\Delta m_d$ are consistent with the corresponding world averages.

We have measured the $B$ CP-violation parameter $\sin 2\phi_1$, the $B_d^0-\overline{B_d^0}$ mixing parameter $\Delta m_d$ and $B$-meson lifetimes using $10.5 fb^{-1}$ of data collected with the Belle detector at KEKB.
Neutral and charged $B$-meson lifetimes are measured to be $\tau(B^0_d) = 1.548 \pm 0.035$ (stat.) ps and $\tau(B^+)=1.656 \pm 0.038$ (stat.) ps. The oscillation frequency $\Delta m_d$ for $B^0_d \to \overline{B}^0_d$ mixing is measured to be $0.522 \pm 0.026$ (stat.) ps$^{-1}$ using semileptonic modes and $0.527 \pm 0.032$ (stat.) ps$^{-1}$ using hadronic modes. The above results are preliminary. The $B$ $CP$-violation parameter $\sin 2\phi_1$ is measured to be

$$\sin 2\phi_1 = 0.58^{+0.32}_{-0.34} \text{ (stat.)}^{+0.09}_{-0.10} \text{ (syst.)}.$$ 

If the true value is 0, the probability to obtain $\sin 2\phi_1 > 0.58$ is 4.9%.

References

1. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
2. A.B. Carter and A.I. Sanda, Phys. Rev. D 23, 1567 (1981); I.I. Bigi and A.I. Sanda, Nucl. Phys. B 193, 85 (1981)
3. H. Quinn and A.I. Sanda, Eur. Phys. Jour. C 15, 626 (2000). (Some papers refer to this angle as $\beta$.)
4. K. Abe et al. (Belle Collab.), The Belle Detector, KEK Report 2000-4, to be published in Nucl. Instrum. Methods.
5. KEKB B Factory Design Report, KEK Report 95-1, 1995, unpublished.
6. Charge conjugate modes are implied throughout this paper.
7. H. Tajima, Measurement of Heavy Meson Lifetimes with Belle, Proceedings of the 30th International Conference on High Energy Physics, July 2000, Osaka. hep-ex/0102016.
8. A. Abashian et al, Phys. Rev. Lett. 86, 2509 (2001).
9. Eur. Phys. Jour. C 15, 1 (2000).