Precise Measurement of $B$ Meson Lifetimes with Hadronic Decay Final States

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Abstract

The lifetimes of the $\bar{B}^0$ and $B^-$ mesons are extracted from 29.1 fb$^{-1}$ of data collected with the Belle detector at the KEK $B$-factory. A fit to the decay length differences of neutral and charged $B$ meson pairs, measured in events where one of the $B$ mesons is fully reconstructed in several hadronic modes, yields $\tau_{\bar{B}^0} = 1.554 \pm 0.030 \text{ (stat)} \pm 0.019 \text{ (syst)}$ ps, $\tau_{B^-} = 1.695 \pm 0.026 \text{ (stat)} \pm 0.015 \text{ (syst)}$ ps, and $\tau_{B^-}/\tau_{\bar{B}^0} = 1.091 \pm 0.023 \text{ (stat)} \pm 0.014 \text{ (syst)}$.

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Lifetime measurements of $\bar{B}^0$ and $B^-$ provide key input to the determination of the Kobayashi-Maskawa matrix element $|V_{cb}|$ [1]. Moreover, the ratio of the lifetimes is sensitive to effects beyond the spectator model. In the framework of heavy quark expansion, the $B$ lifetime ratio is predicted to be equal to one, up to small corrections proportional to $1/m_b^2$ [2], where $m_b$ is the mass of the $b$ quark. A recent theoretical study predicts $\tau_{B^+}/\tau_{\bar{B}^0} = 1.07 \pm 0.03$ [3], which agrees with the world average of measurements, $\tau_{B^+}/\tau_{\bar{B}^0} = 1.073 \pm 0.027$ [4]. The BABAR collaboration recently reported $\tau_{B^+}/\tau_{\bar{B}^0} = 1.082 \pm 0.026 \pm 0.012$ [5]. Accurate determinations of the $\bar{B}^0$ and $B^-$ lifetimes also provide essential input to analyses of CP violation and neutral $B$ mixing.

The analysis described here is based on a 29.1 fb$^{-1}$ data sample, which contains $31.3 \times 10^6$ $B\bar{B}$ pairs, collected with the Belle detector [6] at the asymmetric-energy KEKB collider (8.0 GeV electrons against 3.5 GeV positrons) [7]. Electron-positron annihilations produce $\Upsilon$($4S$) mesons moving along the electron beamline ($z$ axis) with $(\beta\gamma)_\Upsilon = 0.425$, and decaying into $B^0\bar{B}^0$ or $B^+B^-$. Since the $B$ mesons are nearly at rest in the $\Upsilon$($4S$) center of mass system (c.m.), $B$ lifetimes can be determined from the separation in $z$ between the two $B$ decay vertices. The average separation is $c\tau_B(\beta\gamma)_\Upsilon \sim 200$~μm, where $\tau_B$ is the $B$ meson lifetime. In this analysis, one of the $B$ decay vertices is determined from a fully reconstructed $B$ meson, while the other is determined inclusively using the rest of the tracks in the event.

The Belle detector consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of 1188 aerogel Cherenkov counters (ACC), 128 time-of-flight (TOF) scintillation counters, an electromagnetic calorimeter containing 8736 CsI(Tl) crystals (ECL), and 14 layers of 4.7-cm-thick iron plates interleaved with a system of resistive plate counters (KLM). All subdetectors except the KLM are located inside a 3.4 m diameter superconducting solenoid which provides a 1.5 T magnetic field. The impact parameter resolutions for charged tracks are measured to be $\sigma_{xy}^2 = (19)^2 + (50/(p\beta\sin^{3/2}\theta))^2$~mm$^2$ in the plane perpendicular to the $z$ axis and $\sigma_z^2 = (36)^2 + (42/(p\beta\sin^{5/2}\theta))^2$~mm$^2$ along the $z$ axis, where $\beta = pc/E$, $p$ and $E$ are the momentum (GeV/c) and energy (GeV), and $\theta$ is the polar angle from the $z$ axis. The transverse momentum resolution is $(\sigma_{p_t}/p_t)^2 = (0.0030/\beta)^2 + (0.0019p_t)^2$, where $p_t$ is in GeV/c.

$\bar{B}^0$ and $B^-$ mesons are fully reconstructed in the following decay modes: $\bar{B}^0 \to D^+\pi^-, D^+\pi^-\pi^0$, $J/\psi K^0$, $J/\psi K^0\pi^0$, $B^- \to D^0\pi^-$, and $J/\psi K^-$ [6].

Charged pion and kaon candidates are required to satisfy selection criteria based on particle-identification likelihood functions derived from specific ionization $(dE/dx)$ in the CDC, time-of-flight, and the response of the ACC. Electrons are identified using a combination of $dE/dx$, the response of the ACC, and the position, shape, and total energy $(i.e., E/p)$ of their associated ECL showers. Muon candidates must penetrate the iron plates of the KLM in a manner consistent with the muon hypothesis.

The reconstruction and selection criteria for $K^0_S \to \pi^+\pi^-$ and $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$) are described elsewhere [6]. $K^{*0}$ candidates are reconstructed in the $K^{*0} \to K^-\pi^+$ channel and required to have an invariant mass within 75 MeV/$c^2$ of the average $K^{*0}$ mass.

Photon candidates are defined as isolated ECL clusters of more than 20 MeV that are not matched to any charged track. $\pi^0$ candidates are reconstructed from pairs of photon candidates with invariant masses between 124 and 146 MeV/$c^2$. A mass-constrained fit is performed to improve the $\pi^0$ momentum resolution. A minimum $\pi^0$ momentum of 0.2 GeV/c is required. $\rho^-$ candidates are selected as $\pi^-\pi^0$ pairs having invariant masses within 150 MeV/$c^2$ of the average $\rho^-$ mass.

Neutral and charged $D$ candidates are reconstructed in the following channels: $D^0 \to \pi^-\pi^+\pi^0$.
\(K^{-}\pi^+, K^{-}\pi^+\pi^0, K^{-}\pi^+\pi^+\pi^-\), and \(D^+ \rightarrow K^{-}\pi^+\pi^+.\) \(D^{*+} \rightarrow D^0\pi^+\) candidates are formed by combining a \(D^0\) candidate with a slow and positively charged track, for which no particle identification is required.

To reduce continuum background, a selection based on the ratio of the second to zeroth Fox-Wolfram moments and the angle between the thrust axes of the reconstructed and associated \(B\) mesons is applied mode by mode.

The decay vertices of the two \(B\) mesons in each event are fitted using tracks that are associated with at least one SVD hit in the \(r-\phi\) plane and at least two SVD hits in the \(r-z\) plane under the constraint that they are consistent with the interaction point (IP) profile, smeared in the \(r-\phi\) plane by 21 \(\mu\)m, to account for the transverse \(B\) decay length. The IP profile is described as a three-dimensional Gaussian, the parameters of which are determined in each run (every 60,000 events in case of the mean position) using hadronic events. The size of the IP region is typically \(\sigma_x \approx 100 \mu\)m, \(\sigma_y \approx 5 \mu\)m, and \(\sigma_z \approx 3 \)mm, where \(x\) and \(y\) denote horizontal and vertical directions, respectively.

In the case of a fully reconstructed \(\bar{B} \rightarrow D^{(*)}X\) decay, the \(B\) decay point is obtained from the vertex position and momentum vector of the reconstructed \(D\) meson and a track other than the slow \(\pi^+\) candidate from \(D^{*+}\) decay. For a fully reconstructed \(\bar{B} \rightarrow J/\psi X\) decay, the \(B\) vertex is determined using lepton tracks from the \(J/\psi\). The decay vertex of the associated \(B\) meson is determined from tracks not assigned to the fully reconstructed \(B\) meson; however, poorly reconstructed tracks (with a longitudinal position error in excess of 500 \(\mu\)m) as well as tracks likely to come from \(K_S^0\) decays (forming the \(K_S^0\) mass with another track, or more than 500 \(\mu\)m away from the fully reconstructed \(B\) vertex in the \(r-\phi\) plane) are not used.

The quality of the fit is assessed only in the \(z\) direction (because of the tight IP constraint in the transverse plane), using the following variable \(\xi \equiv (1/2n) \sum_i (z_{\text{after}}^i - z_{\text{before}}^i)/\varepsilon_{\text{before}}^i\), where \(n\) is the number of tracks used in the fit, \(z_{\text{before}}^i\) and \(z_{\text{after}}^i\) are the \(z\) positions of each track (at the closest approach to the origin) before and after the vertex fit, respectively, and \(\varepsilon_{\text{before}}^i\) is the error of \(z_{\text{before}}^i\). A Monte Carlo (MC) study shows that \(\xi\) does not depend on the \(B\) decay length. We require \(\xi < 100\) to eliminate poorly reconstructed vertices. About 3% of the fully reconstructed and 1% of the associated \(B\) decay vertices are rejected.

The proper-time difference between the fully-reconstructed and the associated \(B\) decays, \(\Delta t \equiv t_{\text{rec}} - t_{\text{asc}}\), is calculated as \(\Delta t = (z_{\text{rec}} - z_{\text{asc}})/(c(\beta\gamma))\), where \(z_{\text{rec}}\) and \(z_{\text{asc}}\) are the \(z\) coordinates of the fully-reconstructed and associated \(B\) decay vertices, respectively. We reject a small fraction (~0.2%) of the events by requiring \(|\Delta t| < 70\) ps (~45\(\tau_B\)). The final event selection is based on requirements on the energy difference \(\Delta E \equiv E_{\text{beam}}^{\text{cms}} - E_{B}^{\text{cms}}\) and the beam-energy constrained mass \(M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_{B}^{\text{cms}})^2}\), where \(E_{\text{beam}}^{\text{cms}}, E_{B}^{\text{cms}},\) and \(p_{B}^{\text{cms}}\) are the beam energy, the energy, and the momentum of the fully reconstructed \(B\) candidate in the cms, respectively. If more than one fully reconstructed \(B\) candidate is found in the same event, the one with the best \(\chi^2\) for \(\Delta E\) and \(M_{bc}\) (and the invariant mass of the \(D\) candidate for the \(\bar{B} \rightarrow D^{(*)}X\) case) is chosen. For each channel, a square signal region is defined in the \(\Delta E-M_{bc}\) plane, corresponding to \(\pm 3\sigma\) windows centered on the expected means for \(\Delta E\) and \(M_{bc}\). A standard deviation is about 3 MeV/c\(^2\) for \(M_{bc}\) and 10–30 MeV for \(\Delta E\) depending on the decay mode. After all vertexing and selection requirements, we find 7863 \(\bar{B}^0\) and 12047 \(B^-\) events in the \(\Delta E-M_{bc}\) signal region. Figure shows the \(M_{bc}\) distributions for all the \(\bar{B}^0\) and \(B^-\) candidates found in the \(\Delta E\) signal region.

We extract lifetime information using an unbinned maximum likelihood fit to the observed \(\Delta t\) distributions. We maximize the likelihood function \(L = \prod_i P(\Delta t_i),\) where \(P(\Delta t \)is the
probability density function (PDF) for the proper-time difference $\Delta t$ for each event and the product is taken over all selected events. The function $P(\Delta t)$, expressed as

$$P(\Delta t) = (1 - f_{\text{ol}}) [f_{\text{sig}} P_{\text{sig}}(\Delta t) + (1 - f_{\text{sig}}) P_{\text{bkg}}(\Delta t)] + f_{\text{ol}} P_{\text{ol}}(\Delta t),$$  

contains contributions from the signal and the background ($P_{\text{sig}}$ and $P_{\text{bkg}}$), where $P_{\text{sig}}$ is described as the convolution of a true PDF ($P_{\text{sig}}$) with a resolution function ($R_{\text{sig}}$) and $P_{\text{bkg}}$ is expressed in a similar way:

$$P_j(\Delta t) = \int_{-\infty}^{+\infty} d(\Delta t') P_j(\Delta t') R_j(\Delta t - \Delta t'),$$  

where $j = \text{sig, bkg}$. To account for a small number of events that give large $\Delta t$ in both the signal and background (outlier components), we add a third component: $P_{\text{ol}}(\Delta t) = G(\Delta t; \sigma_{\text{ol}})$, where $G(t; \sigma) \equiv \exp(-t^2/(2\sigma^2))/(\sqrt{2\pi}\sigma)$ is the Gaussian function. The global fraction ($f_{\text{ol}}$) and the width ($\sigma_{\text{ol}}$) are left as free parameters in the fit.

The signal purity ($f_{\text{sig}}$) is determined on an event-by-event basis as a function of $\Delta E$ and $M_{bc}$. The two-dimensional distribution of these variables including the sideband region is fitted with the sum of a Gaussian signal function $F_{\text{sig}}(\Delta E, M_{bc})$ and a background function $F_{\text{bkg}}(\Delta E, M_{bc})$, represented as an ARGUS background function [11] in $M_{bc}$ and a first-order polynomial in $\Delta E$. The fraction of signal is then obtained as $f_{\text{sig}}(\Delta E, M_{bc}) = F_{\text{sig}}/[F_{\text{sig}} + F_{\text{bkg}}]$. The true PDF for the signal is given by

$$P_{\text{sig}}(\Delta t) = \frac{1}{2\tau_B} \exp \left( -\frac{|\Delta t|}{\tau_B} \right),$$  

FIG. 1: The beam-energy constrained mass distributions of the fully reconstructed $B$ candidates (neutral on top, charged on bottom). The dashed curves show the background contributions.
where $\tau_B$ is, depending on the reconstructed mode in the event, either the $B^0$ or the $B^-$ lifetime. The resolution function of the signal is constructed as the convolution of four different contributions: the detector resolutions on $z_{\text{rec}}$ and $z_{\text{asc}}$ ($R_{\text{rec}}$ and $R_{\text{asc}}$), an additional smearing on $z_{\text{asc}}$ due to the inclusion of tracks which do not originate from the associated $B$ vertex ($R_{\text{np}}$), mostly due to charm and $K_S$ decays, and the kinematic approximation that the $B$ mesons are at rest in the cms ($R_k$).

For a vertex obtained from a single track, $R_{\text{rec}}$ and $R_{\text{asc}}$ are parameterized as a single Gaussian function, $G(t; (s_0^j + s_1^j\xi_j)\sigma_j)$ ($j = \text{rec}, \text{asc}$) where $\sigma_j$ is the proper-time error estimated vertex-by-vertex from the $z_j$ error, and $(s_0^j + s_1^j\xi_j)$ is a scale factor based on the vertex fit quality $\xi$ defined above. The parameters for the scale factor, $s_0^j$ and $s_1^j$, are determined from the lifetime fit. The typical value of the scale factor is 1.32 for $R_{\text{rec}}$ and 1.20 for $R_{\text{asc}}$. For a vertex obtained from a single track, we use $(1 - f_{\text{tail}})G(t; \sigma_{\text{main}}j) + f_{\text{tail}}G(t; \sigma_{\text{tail}}j),$ where $\sigma_{\text{main}}$ and $\sigma_{\text{tail}}$ are global scaling factors. The shape of $R_{\text{np}}$ is determined from MC data sample, separately for $B^0$ and $B^-$ events. $R_k$ is calculated analytically as a function of $E_B^{\text{ms}}$ and $\cos\theta_B^{\text{ms}}$ from the kinematics of the $\Upsilon(4S)$ two-body decay, where $\theta_B^{\text{ms}}$ is the polar angle of the reconstructed $B$ in the cms. The resulting $\Delta t$ resolution for the signal is $\sim 1.56$ ps (rms).

The background PDF, $P_{\text{bkg}}(\Delta t)$, is modeled as a sum of exponential and prompt components convoluted with $R_{\text{bkg}}(\Delta t) = (1 - f_{\text{tail}})G(\Delta t; \sigma_{\text{rec}}^2 + \sigma_{\text{asc}}^2) + f_{\text{tail}}G(\Delta t; \sigma_{\text{rec}}^2 + \sigma_{\text{asc}}^2)$. Different values are used for $\sigma_{\text{main}}$, $\sigma_{\text{tail}}$, and $f_{\text{tail}}$ depending on whether both vertices are reconstructed with multiple tracks or not. The parameters for the background function $P_{\text{bkg}}$ are determined using the $\Delta E$-$M_{bc}$ sideband region for each decay mode. A MC study shows that the fraction of prompt component in the signal region is smaller (by $\sim 10$–50% depending on the decay mode) than that in the sideband region. We correct $P_{\text{bkg}}$ for this effect.

In the final fit to the events in the signal region, we determine simultaneously 12 parameters: the $B^0$ and $B^-$ lifetimes, 7 parameters for $R_{\text{rec}}$ and $R_{\text{asc}}$, and 3 parameters for the outlier component. We find $\sigma_{\text{ol}} = 36^{+8}_{-5}$ ps, and $f_{\text{ol}} = (0.06^{+0.03}_{-0.02})\%$ or (3.1 ± 0.4)% (multiple- or single-track case). The lifetime ratio, $r \equiv \tau_{B^-}/\tau_{B^0}$, is obtained by repeating the final fit after replacing $\tau_{B^-}$ with $r\tau_{B^0}$. The fit yields $\tau_{B^0} = 1.554 \pm 0.030$ ps, $\tau_{B^-} = 1.695 \pm 0.026$ ps, and $\tau_{B^-}/\tau_{B^0} = 1.091 \pm 0.023$. Figure 3 shows the distributions of $\Delta t$ for the $B^0$ and $B^-$ events in the signal region with the fitted curves superimposed.

The systematic errors are summarized in Table 4. The systematic error due to the IP constraint is estimated by varying (±10 μm) the smearing used to account for the transverse $B$ decay length. The IP profile is determined using two different methods and we find no change in the lifetime results. Possible systematic effects due to the track quality selection of the associated $B$ decay vertices are studied by varying each criterion by 10%. The fit quality criterion for reconstructed vertices is varied from $\xi < 50$ to $\xi < 200$. We estimate the systematic uncertainty due to the maximum $|\Delta t|$ requirement by varying the $|\Delta t|$ range by ±30 ps and taking the maximum excursion to be the systematic error. We examine the uncertainty in the scale of $\Delta t$ arising from the measurement error of the SVD sizes and thermal expansion during the operation, and find that its contribution to the lifetimes is negligibly small. $\Delta E$-$M_{bc}$ signal regions are varied by ±10 MeV for $\Delta E$ and ±3 MeV/c² for $M_{bc}$. The parameters determining $f_{\text{sig}}$ are varied by ±1σ to estimate the associated systematic error. The systematic error due to the modeling of $R_{\text{sig}}$ is estimated by comparing the results with different $R_{\text{sig}}$ parameterizations. The lifetime fit is repeated after varying the
FIG. 2: The \( \Delta t \) distributions of neutral (top) and charged (bottom) \( B \) meson pairs, with fitted curves. The dashed lines represent the sum of the background and outlier component, and the dotted lines represent the outlier component.

TABLE I: Summary of systematic errors for neutral and charged \( B \) lifetimes, and their ratio. The errors are combined in quadrature.

| Source                          | \( \tau_{B^0} \) (ps) | \( \tau_{B^-} \) (ps) | \( \tau_{B^-}/\tau_{B^0} \) |
|--------------------------------|------------------------|------------------------|-----------------------------|
| IP constraint                  | 0.004                  | 0.003                  | 0.001                       |
| Track selection                | 0.006                  | 0.004                  | 0.001                       |
| Vertex selection               | 0.003                  | 0.002                  | 0.002                       |
| \( \Delta t \) range           | 0.003                  | 0.002                  | 0.001                       |
| \( \Delta E-M_{bc} \) signal region | 0.003                  | 0.004                  | 0.003                       |
| Signal fraction                | 0.001                  | 0.001                  | 0.001                       |
| \( R_{\text{sig}} \) parameterization | 0.008                  | 0.008                  | C cancels                   |
| \( R_{\text{np}} \) parameters | 0.006                  | 0.004                  | 0.006                       |
| Background shape               | 0.012                  | 0.007                  | 0.011                       |
| MC statistics                  | 0.006                  | 0.007                  | 0.005                       |
| Total                          | 0.019                  | 0.015                  | 0.014                       |
parameters by $\pm 2\sigma$. The lifetime dependence on the $B$ meson mass, which is the input for $R_k$, is measured by varying the mass by $\pm 1\sigma$ from the world average value and found the differences to be negligible. The systematic error due to the background shape is estimated by varying its parameters by their errors. The possible bias in the fitting procedure and the effect of SVD alignment error are studied with MC samples; we find no bias and include the MC statistics as a systematic error.

To conclude, we have presented new measurements of the $B^0$ and $B^-$ meson lifetimes using $29.1 \text{ fb}^{-1}$ of data collected with the Belle detector near the $\Upsilon(4S)$ energy. Unbinned maximum likelihood fits to the distributions of the proper-time difference between the two $B$ meson decays yield:

\[
\begin{align*}
\tau_{B^0} &= 1.554 \pm 0.030\text{(stat)} \pm 0.019\text{(syst)} \text{ ps}, \\
\tau_{B^-} &= 1.695 \pm 0.026\text{(stat)} \pm 0.015\text{(syst)} \text{ ps}, \text{ and} \\
\tau_{B^-}/\tau_{B^0} &= 1.091 \pm 0.023\text{(stat)} \pm 0.014\text{(syst)}. 
\end{align*}
\]

These are currently the most precise measurements. A value of unity for $\tau_{B^-}/\tau_{B^0}$ is ruled out at a level greater than $3\sigma$ and the measured value is consistent with the theoretical prediction [3].

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[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
[2] I. Bigi, B. Blok, M. Shifman, N. Uraltsev, and A. Vainshtein, in $B$ Decays, Revised 2nd Edition, edited by S. Stone (World Scientific, 1994); M. Neubert and C. T. Sachrajda, Nucl. Phys. B483, 339 (1997).
[3] D. Becirevic, in: Proceeding of the International Europhysics Conference on High-Energy Physics (HEP 2001), Budapest, 2001.
[4] Particle Data Group, D. E. Groom et al., Eur. Phys. J. C 15, 1 (2000) and 2001 partial update for edition 2002 (URL http://pdg.lbl.gov).
[5] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 87, 201803 (2001).
[6] Belle Collaboration, A. Abashian et al., KEK Progress Report No. 2000-4 (2000) (to appear in Nucl. Instrum. Methods Phys. Res.).
[7] KEKB B Factory Design Report, KEK Report No. 95-7 (1995) (unpublished).
[8] Throughout this paper, when a decay mode is quoted the inclusion of charge conjugate mode is implied.
[9] Belle Collaboration, A. Abashian et al., Phys. Rev. Lett. 86, 2509 (2001).
[10] G. C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).
[11] ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B 241, 278 (1990); the ARGUS function is presented as $ax\sqrt{1 - (x/E_{\text{beam}})^2} \exp\left\{ b \left[ 1 - (x/E_{\text{beam}})^2 \right] \right\}$, where $a$ and $b$ are constants that are determined from the data.

[12] The IP constraint enables us to determine a vertex even with a single track. The fraction of such vertices is about 1% for $z_{\text{rec}}$ and 30% for $z_{\text{asc}}$. 

