B-meson lifetimes, $B\overline{B}$ mixing, EPR correlations, CPT and Lorentz violation

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- text forward references ϕ_1, ϕ_2 and global fits

Lifetime and mixing: status and dependencies

14.5 B meson lifetimes and $B^0\overline{B}^0$ mixing

Editors:
Soeren Prell (BABAR)
Bruce Yabsley (Belle)

The charged and neutral B meson lifetimes, τ_{B^+} and τ_{B^0}, and the $B^0\overline{B}^0$ oscillation frequency Δm_d are fundamental parameters of B meson decays. They provide important input for the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{td}|$. In addition, precise knowledge of τ_{B^0} and Δm_d is necessary for the extraction of CP asymmetries from the neutral B decay-time distributions. Here we describe the precision measurements of τ_{B^+}, τ_{B^0} (section 14.5.1), Δm_d (section 14.5.2) and a test of the quantum-mechanical nature of $B^0\overline{B}^0$ oscillations (section 14.5.3) by the B factories.

14.5.1 B meson lifetimes

In 1983, the MAC and MARK II Collaborations (Fernandez et al., 1983; Lockyer et al., 1983) discovered in 29 GeV center-of-mass energy e^+e^- collisions recorded at the PEP storage ring at SLAC that the impact parameters of high-momentum leptons in hadronic final states were largely positive. Assuming these leptons originated mostly from b hadron decays, the collaborations estimated a b hadron lifetime of the order of one picosecond from the measured lepton impact parameter distributions. Such a long lifetime was unexpected at the time. Phenomenological guidance on the strength of weak b hadron decays then was the quark mixing between the first and second quark generation characterized by the Cabibbo angle. If quark mixing between the second and the third generation was similar, a b lifetime of around 0.1 ps was expected (Barger, Long, and Pakvasa, 1979). The long lifetime of b hadrons was the first evidence that the magnitude of the CKM matrix element V_{cb} is much smaller than the Cabibbo angle. Along with first limits on the branching fractions of semileptonic $b \to u$ transitions and thus $|V_{\rm ub}/V_{\rm cb}|$ from experiments at Cornell around the same time (Chen et al., 1984; Klopfenstein et al., 1983) and unitarity constraints, the measurement of $|V_{cb}|$ led to the first complete picture of the magnitudes of all the CKM matrix elements (Ginsparg and Wise, 1983). Soon after, it was realized that due to its long lifetime the B^0 can oscillate into a $\overline{B}^0$ before it decays allowing for measurements of $B^0\overline{B}^0$ mixing and time-dependent CP asymmetries.

At the time when the B factories started to record their first data, the Particle Data Group listed in their 2000 Review of Particle Physics (Groom et al., 2000) the averages of the B^0 and B^+ lifetimes and their ratio as follows: $\tau_{B^0} = (1.548\pm0.032)$ ps, $\tau_{B^+} = (1.653\pm0.028)$ ps, and $\tau_{B^+}/\tau_{B^0} = 1.062 \pm 0.029$ with relative uncertainties of 2.1%, 1.7% and 2.7%, respectively.

While the first measurements of the magnitude of the CKM matrix element V_{cb} were provided by the initial b hadron lifetime measurements, based on advances in the theoretical descriptions of B meson decays the current most precise determination of $|V_{\rm cb}|$ comes from semileptonic branching ratios (see section 14.1).

The main motivations for the B factories to measure the B meson lifetimes even more precisely are two-fold. One reason is theoretical and one is experimental. The spectator quark model predicts that the two charge states of the B meson, B^+ and B^0, have the same lifetime. Deviations from this simple picture are expected to be of order $1/m_b^3$ (Bigi, 1996; Neubert and Sachrajda, 1997), where m_b is the b quark mass. A recent calculation predicts the ratio of the B^+ and B^0 lifetimes to be $\tau_{B^+}/\tau_{B^0} = 1.067 \pm 0.027$ (Becirevic, 2001). While in agreement with this prediction, the data at the time was not conclusive on whether the charged or neutral B lifetime was longer and a more precise measurement of τ_{B^+}/τ_{B^0} would provide a stronger test of these calculations. Experimentally, the B^0 meson lifetime provides an essential input to the measurements of the $B^0\overline{B}^0$ oscillation frequency (see section 14.5.2) and time-dependent CP asymmetries including the angles ϕ_1 and ϕ_2 of the Unitarity Triangle (see sections 14.6 and 14.7). Accurate values of τ_{B^0} and Δm_d reduce the systematic uncertainties in these analyses of time-dependent CP asymmetries.

The most precise measurements of the B meson lifetimes before the first results from the B factories became available were from experiments at the Z^0 resonance and CDF. These experiments measured the distance l the B meson travels from its production point to its decay vertex. The production point is, respectively, the e^+e^- or $p\bar{p}$ interaction point and the decay vertex is determined from the B decay products. From this decay distance l, the measured B momentum p_B, and the known B mass m_B they determine the proper-time of the B meson decay $t = l/c(\beta\gamma)_B = m_B l/(p_B c)$. The proper-time distribution of the B meson candidates is given by $\Gamma(t) = \frac{1}{\tau_B}\exp(-t/\tau_B)$ before accounting for detector resolution and backgrounds. The experiments extract the B meson lifetimes from fits to the measured proper-time spectra. While the ARGUS and CLEO experiments had collected large samples of B mesons at the $\Upsilon(4S)$ resonance, their B mesons were essentially produced at rest in the laboratory frame rendering a proper-time method through decay-length measurements impossible.

These earlier B lifetime measurements are characterized by high-precision proper-time measurements ($\sigma_t \approx xx$), but typically suffered from a combination of relatively small signal samples, large backgrounds, and in the case of partially-reconstructed B mesons, a poor measurement of the B momentum. In contrast, the measurements from *BABAR* and Belle have worse proper-time resolution, but their high-statistics B samples have little background and excellent knowledge of the B momentum.

A principal difference between the B meson lifetime measurements at previous experiments and at the asymmetric-energy B factories is the knowledge of the B production point. At all experiments the B mesons are produced in the luminous region of the particle beams (beam spot). The coordinates of the beam spot are well known. The beam spot size is much smaller in the plane transverse to the beam direction than along the beam direction. At the LEP experiments, SLD and CDF most B mesons travel a measureable distance in the transverse plane before they decay and from this distance the B meson proper-time is derived. In fits to the proper-time distributions, events with measured $t < 0$ provide valuable information about the proper-time resolution function. Since there are no true negative proper-times, all events with measured $t < 0$ are due to resolution effects. In contrast, at the B factories the B mesons are barely moving in the center-of-mass frame. Thus their transverse momentum and transverse flight distance are close to zero and cannot be used for a precise proper-time measurement. The length of the beam spot in the z direction is about a centimeter in *BABAR* and Belle and there are no fragmentation tracks coming from the B production point (as only a $B\bar{B}$-pair is produced in the decay of the $\Upsilon(4S)$), which would allow one to reconstruct the z coordinate. Therefore the z coordinate of the B production vertex cannot be reconstructed with good precision. Instead at the B factories the distance Δz between the decay vertices of the two B mesons is measured. A proper-time difference is then given to good approximation by

$$\Delta t = \Delta z/(c(\beta\gamma)_B), \tag{14.5.1}$$

where $(\beta\gamma)_B$ is the Lorentz boost factor of the B meson in the lab frame (see section 4.5). The Δt distribution is given by

$$\Gamma(\Delta t) = \frac{1}{2\tau_B}\exp\left(-|\Delta t|/\tau_B\right). \tag{14.5.2}$$

It is symmetric around $\Delta t = 0$. Detector resolution effects will smear this distribution, but there is no region in Δt that allows a similarly clean access to the Δt resolution function as in the experiments at the Z^0 and CDF (see Fig. 63). One of the challenges of the B lifetime measurements at the B factories is to disentangle the underlying true Δt distribution from the resolution function.

Both *BABAR* and Belle use multiple samples of B mesons to determine the B^0 and B^+ lifetimes and their ratio. One of the B mesons, $B_{\rm rec}$ is typically reconstructed in an exclusive final state. The various samples differ in their B meson yield per inverse femtobarn and in their signal purity. More exclusive samples have less background, but also a smaller yield. In the lifetime analyses, the z position of the $B_{\rm rec}$ decay vertex $z_{\rm rec}$ is determined from its decay products. The z position, $z_{\rm oth}$ of the decay vertex of the other B meson, $B_{\rm oth}$ is reconstructed from the tracks not belonging to $B_{\rm rec}$. The proper-time difference Δt is then calculated from $\Delta z = z_{\rm rec} - z_{\rm oth}$ using Eq. 14.5.1. It turns out that the uncertainty in Δt is dominated by the uncertainty in $z_{\rm oth}$ and almost the same for all lifetime analyses at the B factories. The B lifetimes are extracted from a fit to the Δt distributions of the selected candidates after accounting for detector resolution effects and background. In the following, we will briefly describe the various measurements of the B meson lifetimes by the B factories. The results of these analyses are summarized in Table 24.

Fully-reconstructed final states

The B lifetime measurements with samples in which one B decays to an exclusive hadronic final states have the lowest background. *BABAR* measures the B^0 and B^+ lifetimes with the hadronic decays $B^0 \to D^{(*)-}\pi^+, D^{(*)-}\rho^+, D^{(*)-}a_1^+, J/\psi K^{*0}$ and $B^+ \to \bar{D}^{(*)0}\pi^+, J/\psi K^+, \psi(2S)K^+$

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Table 24. B factory measurements of τ_{B^0}, τ_{B^+} and τ_{B^0}/τ_{B^+} along with the journal paper, selected final state, signal purity, B meson signal yield, Δz resolution, and integrated luminosity for each measurement.

Neutral B meson lifetime τ_{B0}						
Experiment	Method	$f_{\rm sig.}$	Yield $[B/\,{\rm fb}^{-1}]$	Δz RMS	$\int \mathcal{L}\, dt$	τ_{B0} [ps]
BaBar (Aubert, 2001c)	Excl. hadronic modes	90%	291	190 μm	21 fb^{-1}	$1.546 \pm 0.032 \pm 0.022$
BaBar (Aubert, 2003b)	Incl. $D^*\pi$, $D^*\rho$		603		21 fb^{-1}	$1.533 \pm 0.034 \pm 0.038$
BaBar (Aubert, 2003g)	Excl. $D^*l\nu$	76%	680	175 μm	21 fb^{-1}	$1.523^{+0.024}_{-0.023} \pm 0.022$
BaBar (Aubert, 2002d)	Incl. $D^*l\nu$	53%	4430	? μm	21 fb^{-1}	$1.529 \pm 0.012 \pm 0.029$
BaBar (Aubert, 2006l)	Incl. $D^*l\nu$	64%	605	182 μm	81 fb^{-1}	$1.504 \pm 0.013^{+0.018}_{-0.013}$
Belle (Abe, 2002e)	Excl. hadronic modes	?%	?	? μm	29 fb^{-1}	$1.554 \pm 0.030 \pm 0.019$
Belle (Abe, 2005c)	Excl. had. modes + $D^*l\nu$	81%	707	190 μm	140 fb^{-1}	$1.534 \pm 0.008 \pm 0.010$
Charged B meson lifetime τ_{B+}						
Experiment	Method	$f_{\rm sig.}$	Yield $[B/\,{\rm fb}^{-1}]$	Δz RMS	$\int \mathcal{L}\, dt$	τ_{B+} [ps]
BaBar (Aubert, 2001c)	Excl. hadronic modes	93%	304	190 μm	21 fb^{-1}	$1.673 \pm 0.032 \pm 0.023$
Belle (Abe, 2002e)	Excl. hadronic modes	?%	?	? μm	29 fb^{-1}	$1.695 \pm 0.026 \pm 0.015$
Belle (Abe, 2005c)	Excl. hadronic modes	81%	319	190 μm	140 fb^{-1}	$1.635 \pm 0.011 \pm 0.011$
τ_{B+}/τ_{B0}						
Experiment	Method	$f_{\rm sig.}$	Yield $[B/\,{\rm fb}^{-1}]$	Δz RMS	$\int \mathcal{L}\, dt$	τ_{B+}/τ_{B0}
BaBar (Aubert, 2001c)	Excl. hadronic modes	93%, 90%	304, 291	190 μm	21 fb^{-1}	$1.082 \pm 0.026 \pm 0.012$
Belle (Abe, 2002e)	Excl. hadronic modes	?%	?	? μm	29 fb^{-1}	$1.091 \pm 0.023 \pm 0.014$
Belle (Abe, 2005c)	Excl. had. modes + $D^*l\nu$	81%, 81%	319, 707	190 μm	140 fb^{-1}	$1.066 \pm 0.008 \pm 0.008$

in a data sample of 20.6 fb^{-1} (Aubert, 2001c). Belle performs an analysis combining the exclusive hadronic final states $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $J/\psi K^0_S$, $J/\psi K^{*0}$ to measure the B^0 lifetime and the modes $B^+ \to \overline{D}^0\pi^+$, $J/\psi K^+$ to measure the B^+ lifetime in a sample of 29.1 fb^{-1} (Abe, 2002e). The decay channels $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, and $K^0_S\pi^+\pi^-$ are used to reconstruct $\overline{D}^0$ candidates, while the modes $K^+\pi^-\pi^+$ and $K^0_S\pi^-$ are used for D^- candidates (Belle does not use the D decay modes involving a K^0_S). Charged D^{*-} candidates are formed by combining a $\overline{D}^0$ with a soft π^-. The B^0 candidates are formed by combining a D^{*-} or D^- with a π^+, ρ^+ ($\rho^+ \to \pi^+\pi^0$) or a_1^+ ($a_1^+ \to \pi^+\pi^-\pi^+$). The $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ candidates are reconstructed from combinations of a J/ψ or a $\psi(2S)$ candidate, in the decay modes e^+e^- and $\mu^+\mu^-$, with a K^{*0} ($K^{*0} \to K^+\pi^-$). The $\psi(2S)$ candidates are reconstructed in their decays to $J/\psi\pi^+\pi^-$. In these measurements, the collaborations impose constraints on the B candidates requiring them to be compatible with one of the final states mentioned above. The corresponding branching fractions for the B and D decays to these final states are at most a few percent. Therefore, the selected signal samples have relatively small B^0 (B^+) yields of 291 (304) and ? (?) $B/\,{\rm fb}^{-1}$ for BABAR and Belle, respectively. Due to the tight selection criteria, a main background in other analyses that arises from incorrect combinations of tracks is highly suppressed leading to event samples with high average signal purities of 80–90%.

The z position of the decay vertex, $z_{\rm rec}$, of the fully-reconstructed B meson, $B_{\rm rec}$, is measured with high precision, typically of the order of $\sigma(z_{\rm rec}) \sim 50\ \mu$m. The decay vertex position of the other B, $z_{\rm oth}$, is determined from all tracks not belonging to $B_{\rm rec}$ as described in section 4. For these samples, the $z_{\rm rec}$ resolution is 100–200 μm with an RMS value of about 170 μm. Thus, the Δz resolution is dominated by the resolution of $z_{\rm oth}$. It is similar for all decay modes ($\sigma(\Delta z) = 180 - 190\ \mu$m). Belle converts the measured Δz is into a Δt value according to Eq. 14.5.1, whereas in fully-reconstructed decays BABAR uses a more precise approximation by exploiting the precise knowledge of the B flight direction to correct for the B momentum in the $\Upsilon(4S)$ frame (Eq. 4.5.3). The Δt distributions of the selected B^0 and B^+ candidates are then fit to a likelihood function that describes the true Δt distribution of the signal events (Eq. 14.5.2) convolved with a Δt signal resolution function $\mathcal{R}_{\rm sig}$ to account for the uncertainty in the Δt measurements and an empirical Δt distribution of the background events. BABAR uses a signal Δt resolution function $\mathcal{R}_{\rm sig}$ consisting of the sum of a Gaussian distribution with zero mean and its convolution with a exponential decay that models the bias of $z_{\rm oth}$ due to tracks originating from a displaced decay vertex of a charm meson. Charged and neutral B decays are described with the same Δt resolution function. Belle's signal Δt resolution function $\mathcal{R}_{\rm sig}$ is formed by the convolution of four components: the detector resolutions for $z_{\rm rec}$ and $z_{\rm oth}$, the bias in $z_{\rm oth}$ due to tracks originating from the decay of a charm meson and the kinematic approximation that the B mesons are at rest in the center-of-mass frame (Tajima et al., 2004). Both resolution functions have a term accounting for a small number of poorly reconstructed vertices, so-called Δt outliers. Both experiments describe the background Δt distribution with a prompt term and a term with an effective background lifetime. The background Δt resolution functions are of the same form as the signal resolution functions, but with separate parameters in order to minimize correlations with the signal resolution parameters.

BABAR and Belle determine the values of τ_{B^0} and τ_{B^+} from a simultaenous fit to the samples of B^0 and B^+ can-

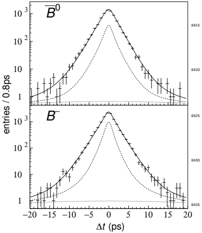

Fig. 63. The Δt distributions of $\overline{B}^0$ (top) and B^- (bottom) candidates for fully-reconstructed B decays to hadronic final states. The dashed lines represent the sum of the background and outlier components, and the dotted lines represent the outlier component (Abe, 2002e).

didates. BABAR measures $\tau_{B^0} = (1.546 \pm 0.0032 \pm 0.022)$ ps and $\tau_{B^+} = (1.673 \pm 0.0032 \pm 0.023)$ ps while Belle measures $\tau_{B^0} = (1.554 \pm 0.0030 \pm 0.019)$ ps and $\tau_{B^+} = (1.695 \pm 0.0026 \pm 0.015)$ ps. The measurements of the B^0 and the B^+ lifetimes share the same sources of systematic uncertainty. Some of these uncertainites cancel in the ratio of the lifetimes $r_\tau \equiv \tau_{B^+}/\tau_{B^0}$. In a separate fit the parameter τ_{B^+} is replaced with $r_\tau \cdot \tau_{B^0}$ to estimate the statistical error of the lifetime ratio. BABAR and Belle measure, respectively, $\tau_{B^+}/\tau_{B^0} = 1.082 \pm 0.026 \pm 0.012$ and $\tau_{B^+}/\tau_{B^0} = 1.091 \pm 0.023 \pm 0.014$. The largest contributions to the systematic uncertainties in the measured lifetimes come from the modeling of the signal Δt resolution function (0.009 – 0.014 ps) and the background Δt distribution (0.005 – 0.012 ps), the alignment of the vertex detector (0.008 ps), the knowledge of the z scale of the detector (0.008 ps), and MC statistics (0.007 – 0.009 ps). The dominant contributions to the systematic error in r_τ come from MC statistics (0.005 – 0.006) and uncertainties in the background Δt distributions (0.005 – 0.011) and the signal Δt resolution function (0.006 – 0.008).

In another analysis BABAR uses events reconstructed in the semileptonic decay $B^0 \to D^{*-}l^+\nu$ ($l = e, \mu$) to determine the B^0 lifetime (Aubert, 2003g). The B yield is larger than for the hadronic final state analysis due to the large B semileptonic branching fraction. They reconstruct 680 $B/\,{\rm fb}^{-1}$. Due to the missing neutrino the background level is higher than in the sample of fully-reconstructed hadronic B decays. The combinatorial D^{*-} background is about 18% and the sum of the backgrounds from events where the D^{*-} and the lepton come from different Bs, events with a fake lepton candidate and events from continuum $c\overline{c} \to D^{*-}X$ processes add up to $5 - 8\%$ depending on the lepton flavor. In this analysis, BABAR simultaneously fits for τ_{B^0} and the $B^0\overline{B}^0$ mixing frequency Δm_d (see also section 14.5.2). Because of the different Δt distributions for mixed events ($B^0\ B^0$ or $\overline{B}^0\ \overline{B}^0$) and unmixed ($B^0\overline{B}^0$) events, separately fitting the two Δt distributions enhances the sensitivity to the signal Δt resolution function. As a result the uncertainty of τ_{B^0} is reduced by approximately 15%. BABAR measures the B^0 lifetime to be $\tau_{B^0} = (1.523^{+0.024}_{0.023} \pm 0.022)$ ps. The dominant systematic error sources are the same as for the analyses of the hadronic final states and similar in size. A large additional systematic uncertainty in the τ_{B^0} measurement comes from the limited statistical precision in determining the bias due to the background modeling. By comparing the fitted τ_{B^0} in simulated events BABAR observes a shift of (0.022 ± 0.009) ps between a signal-only sample and a signal-plus-background sample. The measured B^0 lifetime is corrected for the observed bias from the fit to the MC sample with background and the full statistical uncertainty of ± 0.018 ps is assigned a systematic uncertainty.

Belle performs a measurement of the B lifetimes and their ratio also in a larger sample of 140 fb^{-1} (Abe, 2005c). In this analysis they reconstruct B^0 and B^+ candidates in the same hadronic decay modes as in their previous analysis. In addition they reconstruct B^0 candidates in the semileptonic decay $B^0 \to D^{*-}l^+\nu$. Using a fit to the Δt distributions of the signal candidates they determine the B^0 and B^+ lifetimes and the $B^0\overline{B}^0$ mixing frequency Δm_d simultaneously. The analysis is described in more detail in section 14.5.2. Belle measures $\tau_{B^0} = (1.534 \pm 0.008 \pm 0.010)$ ps, $\tau_{B^+} = (1.635 \pm 0.011 \pm 0.011)$ ps and $\tau_{B^+}/\tau_{B^0} = 1.066 \pm 0.008 \pm 0.008$. The largest contributions to the systematic uncertainties in the measured lifetimes come from unceertainites in the the vertex reconstruction (0.005 – 0.007 ps) and the modeling of the background (0.007 ps). The dominant contributions to the systematic error in r_τ come from uncertainties in the background Δt distributions (0.005) and the signal Δt resolution function (0.004).

Partially-reconstructed final states

BABAR also measures the B^0 meson lifetime in a sample of 21 fb^{-1} using the decay modes $B^0 \to D^{*-}l^+\nu$ (Aubert, 2002d) and $B^0 \to D^{*-}\pi^+$, $B^0 \to D^{*-}\rho^+$ (Aubert, 2003b) with a partially-reconstructed D^{*-} in the final state. These measurements serve as a proof-of-principle for the analyses of the time-dependent CP asymmetries in $B \to D^{(*)\mp}\pi^\pm$ to extract $\sin(2\phi_1 + \phi_3)$ (see section 14.8.5).

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In the measurement of τ_{B^0} with $B^0 \to D^{*-}l^+\nu$ decays they require a high-momentum lepton ($1.4 < p^*_l < 2.3$ GeV/c) and an opposite-charge soft pion (π_s)consistent with coming from the decay $D^{*-} \to \overline{D}^0\pi^-$ ($p^*_{\pi_s} < 0.19$ GeV/c). The D^{*-} momentum is inferred from the π_s momentum without reconstructing the $\overline{D}^0$. The analysis of this inclusive final state does not suffer from the small $\overline{D}^0$ branching fractions to exclusive final states and consequently has a large B yield (4430 B/fb^{-1}). However, without the additional constraints from the $\overline{D}^0$ reconstruction the signal fraction of the selected B cabdidates is only 53%. The $B_{\rm rec}$ decay vertex is calculated from the lepton and π_s tracks and the beam spot. The decay point of the $B_{\rm oth}$ is determined from the remaining tracks in the event. In events that have another high-momentum lepton ($p^*_l > 1.1$ GeV/c) the B vertex is calculated from this lepton track constrained to the beam spot in the transverse plane. Otherwise, all tracks with a center-of-mass angle greater than 90° with respect to the π_s direction are considered. This requirement removes most of the tracks from the decay of the $\overline{D}^0$ daughter of the D^{*-}, which would otherwise bias the reconstruction of the $B_{\rm oth}$ vertex position. Tracks are removed if they contribute more than 6 to the vertex χ^2. *BABAR* measures the B^0 lifetime with a binned maximum likelihood fit to the Δt and $\sigma_{\Delta t}$ distributions of the selected B candidates to be $\tau_{B^0} = (1.529 \pm 0.012 \pm 0.029)$ ps. For this result, the fitted B^0 lifetime is multiplied by a correction factor $\mathcal{R}_{\overline{D}^0} = 1.032 \pm 0.007 \pm 0.007$ to account for daughter tracks of the $\overline{D}^0$ included in the calculation of the $B_{\rm oth}$ decay vertex. The largest systematic uncertainties in τ_{B^0} are due to the knowledge of the fractions and parametrizations of the background types (0.015 ps), the Δt resolution model (0.017 ps) and $\mathcal{R}_{\overline{D}^0}$ (0.015 ps).

In a more recent analysis with 81 fb^{-1}, *BABAR* uses $B^0 \to D^{*-}l^+\nu$ decays with a partially-reconstructed D^{*-} *BABAR* to measure τ_{B^0} and the $B^0\overline{B}^0$ oscillation frequency Δm_d (Aubert, 2006l). They require the other B^0 in the event $B_{\rm oth}$ also to decay semileptonically and determine its decay vertex by constraining the high-energy lepton to the beam spot. After correcting for a small bias (-0.006 ps) observed in MC-simulated events they measure τ_{B^0} = $(1.504 \pm 0.013^{+0.018}_{-0.013})$ ps. The dominant contributions to the systematic error in τ_{B^0} come from uncertainties in the alignment ($^{+0.013}_{-0.004}$ ps) and z scale (0.007 ps) of the SVT and MC statistics (0.007 ps).

BABAR also measures the B^0 lifetime with a partially-reconstructed D^{*-} in the decays $B^0 \to D^{*-}h^+$, where h^+ is either a π^+ or a ρ^+. Similarly to the partial reconstruction of the semi-leptonic final state, they reconstruct only the soft pion π_s from the decay $D^{*-} \to \overline{D}^0\pi^-_s$ and the D^{*-} momentum is inferred from the π_s momentum. The main variable to suppress background in this analysis is the missing $\overline{D}^0$ mass $m_{\rm miss}$, which peaks at the nominal D^0 mass with a spread of 3 MeV/c^2 for $B^0 \to D^{*-}\pi^+$ and 3.5 MeV/c^2 for $B^0 \to D^{*-}\rho^+$. Additional variables to suppress backgrounds include the angle between h and the B^0, the D^{*-} and ρ^+ helicity angles and event shape variables. After all selection requirements are applied, the signal purity is approximately ? %. The dominant background comes continuum events. The remaining background from $B\overline{B}$ events is due to random h and π_s combinations and feed-down from $B \to D^{**}\pi$ events and respectively, from $B^0 \to D^{*-}\rho^+$ to $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}a_1^+$ to $B^0 \to D^{*-}\rho^+$. The z position of the B^0 decay vertex is determined from the h and π_s track constrained to the nominal beam spot. The decay vertex of $B_{\rm oth}$ is determined in the same way as in the *BABAR*'s early analysis of $B^0 \to D^{*-}l^+\nu$ (Aubert, 2002d). For the mode $B^0 \to D^{*-}\pi^+$ they calculate an event-by-event Δz correction to account for tracks from the $\overline{D}^0$ included in the vertex of $B_{\rm oth}$. In both modes a small additional correction to the fitted B^0 lifetime is applied. *BABAR* uses several data control samples to determine the different background fractions in the signal sample and their PDF parameters. These parameters are fixed in the fit to the signal sample. The fitted lifetimes are $\tau_{B^0} = (1.510 \pm 0.040 \pm 0.041)$ ps in $B^0 \to D^{*-}\pi^+$ and $\tau_{B^0} = (1.616 \pm 0.064 \pm 0.075)$ ps in $B^0 \to D^{*-}\rho^+$. The combined result accounting for correlated errors is $\tau_{B^0} = (1.533 \pm 0.034 \pm 0.038)$ ps. *BABAR* quotes only the systematic uncertainties for the individual τ_{B^0} measurements. The dominant uncertainties in the measurements with the modes $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ come from the knowledge of the composition of the background and its PDF parameters (0.024 ps, 0.050 ps), limited MC statistics (0.021 ps, 0.042 ps) and the $\overline{D}^0$ track bias (0.017 ps, 0.026 ps).

Averages of τ_{B^0}, τ_{B^+} and τ_{B^+}/τ_{B^0}

The world averages of the B^0 and B^+ lifetimes and their ratio are calculated by HFAG from the *BABAR* measurements in (Aubert, 2001c, 2002d, 2003b,g, 2006l), the Belle measurements in (Abe, 2005c) and measurements from ALEPH, DELPHI, L3, OPAL, SLD, CDF and DØ (Asner et al., 2010) to be, respectively, $\tau_{B^0} = (1.518 \pm 0.007)$ ps, $\tau_{B^+} = (1.641 \pm 0.008)$ ps and $\tau_{B^+}/\tau_{B^0} = (1.081 \pm 0.006)$ ps. The most precise measurements contributing to these averages come from the B Factories and a recent set of measurements from CDF using fully-reconstructed $B \to J/\psi K^{(*)}$ events (Aaltonen et al., 2011a). DØ provides a precise measurement of τ_{B^+}/τ_{B^0} from samples of $B \to D^{*+}\mu$ and $B \to D^0\mu$ (Abazov et al., 2005). From using only the B Factories measurements, one obtains the averages $\tau_{B^0} = (?\pm?)$ ps, $\tau_{B^+} = (?\pm?)$ ps and $\tau_{B^+}/\tau_{B^0} = (?\pm?)$ ps.

The measurements of the charged and neutral B lifetimes and their ratio now have errors of about half a percent and the B^+ lifetime is now measured to be larger than the B^0 lifetime by many standard deviations. The precision in these measurements exceedes that of existing theoretical calculations. Thus, with the original motivations fully addressed by the current set of measurements and the multitude of relevant systematic error sources that come with sub-percent precision measurements, it is unlikley that there will be improved measurements using the full data set of the B factories or the even larger data sets of future Super B factories.

14.5.2 $B^0\overline{B}^0$ mixing

14.5.2.1 Measurements of Δm_d

Neutral meson-antimeson oscillations were predicted in 1955 by Gell-Mann and Pais (Gell-Mann and Pais, 1955) and first observed in 1956 in the $K^0\overline{K}^0$ system (Lande, Booth, Impeduglia, Lederman, and Chinowsky, 1956). Mixing in the $B^0\overline{B}^0$ system was discovered in 1987 by the ARGUS collaboration (Albrecht et al., 1987) and in the $B^0_s\overline{B}^0_s$ system in 2006 by the CDF collaboration (Abulencia et al., 2006).

Meson-antimeson oscillations proceed through a second order weak interaction as described by a box diagram. The time-evolution of the $B^0\overline{B}^0$ system is given by a phenomenology-based 2×2 Hamiltonian matrix (for details see section 7). Solving this system of equations gives the time-dependent probabilities for $B^0\overline{B}^0$ oscillations. For a $\overline{B}^0$ decay to a flavor eigenstate that is not accessible from a B^0 decay (e.g. the semileptonic decay $\overline{B}^0 \to D^{*+}l^-\nu_l$) the λ in Eqs 7.2.2-7.2.3 is zero. Thus the probability that a B^0 produced at time $t = 0$ decays as $\overline{B}^0$ at time t is given by

$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{e^{-t/\tau_{B^0}}}{2\tau_{B^0}} \times (1 - \cos\Delta m_d t), \quad (14.5.3)$$

where Δm_d is the $B^0\overline{B}^0$ oscillation frequency and τ_{B^0} is the neutral B lifetime. The probability that a produced B^0 decays as B^0 (for example through $B^0 \to D^{*-}l^+\bar{\nu}_l$) is given by

$$\mathrm{Prob}(B^0 \to B^0) = \frac{e^{-t/\tau_{B^0}}}{2\tau_{B^0}} \times (1 + \cos\Delta m_d t). \quad (14.5.4)$$

Likewise the probabilities for a produced $\overline{B}^0$ to decay as a B^0 or a $\overline{B}^0$ are given, respectively, by

$$\mathrm{Prob}(\overline{B}^0 \to B^0) = \frac{e^{-t/\tau_{B^0}}}{2\tau_{B^0}} \times (1 - \cos\Delta m_d t). \quad (14.5.5)$$

and

$$\mathrm{Prob}(\overline{B}^0 \to \overline{B}^0) = \frac{e^{-t/\tau_{B^0}}}{2\tau_{B^0}} \times (1 + \cos\Delta m_d t), \quad (14.5.6)$$

The first measurements of $B^0\overline{B}^0$ oscillations were time-integrated measurements by ARGUS (Albrecht et al., 1987) and CLEO (Artuso et al., 1989). They measured the time-integrated probability χ_d that a B^0 ($\overline{B}^0$) produced in $\Upsilon(4S) \to B^0\overline{B}^0$ decays as a $\overline{B}^0$ (B^0),

$$\chi_d = \frac{x_d^2}{2\,(1 + x_d^2)}, \quad (14.5.7)$$

where $x_d = \Delta m_d/\Gamma_d = \Delta m_d \tau_{B^0}$. In 1993 the LEP experiments started to provide the first time-dependent measurements of Δm_d made possible by their precision vertex detectors and highly-boosted B^0 mesons from Z^0 decays (Abreu et al., 1994; Acciarri et al., 1996; Akers et al., 1994; Buskulic et al., 1993b). The CDF collaboration published their first Δm_d measurement in 1998 (Abe et al., 1998). In the 2000 Review of Particle Physics (Groom et al., 2000) the PDG calculates an average $B^0\overline{B}^0$ oscillation frequency from time-dependent measurements by the LEP experiments and CDF of $\Delta m_d = (0.478 \pm 0.018)\ \mathrm{ps}^{-1}$. If they include measurements of the time-integrated $B^0\overline{B}^0$ mixing probability χ_d from CLEO and ARGUS the PDG obtains a value of $\Delta m_d = (0.472 \pm 0.017)\ \mathrm{ps}^{-1}$.

The experimental strengths and weaknesses in the measurements of Δm_d between the B factories on one side and the LEP experiments and CDF on the other side are the same as for the measurements of the B meson lifetimes. The former benefitted from high-precision proper-time measurements, whereas the latter have the advantage of low-background, high-statistics B samples and excellent B momentum resolution.

One of the first measurements from the B factories was the precise time-dependent measurement of Δm_d. The experimental aspects of this analysis are almost identical to the measurement of time-dependent *CP*-asymmetries (see the measurement of $\sin 2\phi_1$ in section 14.6) in B decays to *CP* eigenstates. In particular, fully-reconstructed B decays to flavor final states, $B_{\rm flav}$, such as $\overline{B}^0 \to D^{(*)+}\pi^-$ have the same B vertex resolutions and thus Δt resolution function as B decays to $(c\bar{c})s$ *CP* eigenstates, B_{CP} (see sections 4 and 14.6). The same B flavor-tagging algorithms are used to determine the flavors of $B_{\rm flav}$ and B_{CP} at the time of their production (see section 5.3). In both cases, maximum likelihood fits are used to extract the parameters of the time-dependent asymmetries from the measured Δt distributions. A by-product of the Δm_d measurement with fully-reconstructed final states are the B flavor-tagging mistag rates, which cannot be determined with *CP* eigenstates. In additon, a confirmation of the Δm_d results of previous experiments served as a convincing proof-of-principle of this novel technique for measuring time-dependent *CP* asymmetries at the asymmetric beam-energy B factories. On the other hand, improving the knowledge of Δm_d has been and still is interesting in its own right. The oscillation frequency Δm_d is proportional to $|V_{\rm td}|^2$ and a precise Δm_d measurement along with a measurement of the $B_s\overline{B}_s$ oscillation frequency Δm_s from hadron colliders and lattice QCD calculations of the decay constants and QCD bag parameters of B^0 and B_s mesons (for details see section 14.2) provide strong constraints on the Unitarity Triangle (see section 22.1).

The time-dependent Δm_d measurements by the B factories all follow the same basic idea. In the $\Upsilon(4S) \to B^0\overline{B}^0$ decay the two neutral B mesons are produced in a coherent P-wave state. If one of the B mesons, referred to as $B_{\rm tag}$, can be ascertained to decay to a state of known flavor, i.e. B^0 or $\overline{B}^0$, at a certain time $t_{\rm tag}$, the other B referred to as $B_{\rm rec}$, at that time must be of the opposite

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flavor as a consequence of Bose symmetry. Consequently, the probabilities to observe *unmixed* (+), $B^0\overline{B}^0$, or *mixed* (−), B^0B^0 and $\overline{B}^0\overline{B}^0$, events are functions of the proper-time difference $\Delta t = t_{\rm rec} - t_{\rm tag}$ and of Δm_d:

$$\mathrm{Prob}(B^0\overline{B}^0 \to B^0\overline{B}^0) \equiv P_+(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times (1+\cos\Delta m_d\Delta t),$$

$$\mathrm{Prob}(B^0\overline{B}^0 \to B^0B^0 \text{ or } \overline{B}^0\overline{B}^0) \equiv P_-(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times (1-\cos\Delta m_d\Delta t). \quad (14.5.8)$$

The B factories have measured the $B^0\overline{B}^0$ oscillation frequency with various final states and B recontruction techniques. In all Δm_d measurements one B is reconstructed in a specific flavor final state, $B_{\rm rec}$, while the remaining charged particles in the event are used to identify, or "tag" the flavor of the other B, referred to as $B_{\rm tag}$, as a B^0 or $\overline{B}^0$. In the analyses of dilepton final states, both B mesons are identified only through high-momentum leptons from semileptonic decays. The proper-time difference $\Delta t = \Delta z/\langle\beta\gamma\rangle c$ is determined from the z positions of the B decay vertices $\Delta z = z_{\rm rec} - z_{\rm tag}$ and the average boost of the $\Upsilon(4S)$ frame in the lab frame $\langle\beta\gamma\rangle$. The boost is known to good precision from the e^+ and e^- beam energies and the Δz measurement dominates the Δt resolution (see section 4). The value of Δm_d is then extracted from a simultaneous fit to the Δt distributions of the unmixed and mixed events. There are two principal experimental complications to the probability distributions in Eq. 14.5.8. First, the flavor tagging algorithm sometimes incorrectly identifies the $B_{\rm tag}$ flavor. The probability to incorrectly identify the flavor of $B_{\rm tag}$, w reduces the observed amplitude for the oscillation by a factor $(1-2w)$. Second, the resolution of Δt is comparable to the oscillation period and must be accounted for. The PDFs for the unmixed and mixed signal events $\mathcal{H}_{\pm,\rm sig}$ can be expressed as the convolution of the underlying Δt distribution

$$h_{\pm,\rm sig}(\Delta t;\Delta m_d,w) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm (1-2w)\cos\Delta m_d\Delta t\right], \quad (14.5.9)$$

with a signal Δt resolution function $\mathcal{R}_{\rm sig}$ containing parameters $\hat{a}_j$. A fit is then performed to extract simultaneously mistag rates w, the resolution function parameters $\hat{a}_j$, and the mixing frequency Δm_d. In the remainder of this section we give brief descriptions of the various Δm_d measurements by the B factories. The results are summarized in Table 25.

Dilepton final states

Belle published their first measurement of Δm_d using dilepton events in a sample of 5.9 fb^{-1} (Abe, 2001b). In a later ananlysis of the same final state, they used a sample of 29 fb^{-1} (Hastings, 2003). *BABAR* published one measurement of Δm_d with dilepton events using a sample of 21 fb^{-1} (Aubert, 2002c).

The inclusive nature of the dilepton final state provides large event samples. The measurements are based on the identification of events containing lepton pairs (e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$) from semileptonic decays of B mesons. The flavors of the B mesons when they decay are determined or "tagged" by the charges of the leptons in the final state. For $\Upsilon(4S)$ resonance decays into $B^0\overline{B}^0$ pairs, opposite-sign charge (OS) and same-sign charge (SS) lepton pairs correspond to unmixed and mixed events, respectively. Both experiments apply selection criteria ensure a well-measured Δt and to suppress backgrounds from fake leptons, continuum events, J/ψ decays and so-called B cascade decays, where a lepton originates from the semileptonic decay of a charm meson, which can come from the same or the opposite B as the other lepton. An irreducible background comes from charged B pairs.

Belle determines the z coordinates of the B decay vertices from the intersections of the lepton tracks with the profile of the beam interaction point (IP) convolved with the average B^0 flight length (~20 μm in the $\Upsilon(4S)$ rest frame). The mean position and width are determined on a run-by-run basis using hadronic events (see section 4). They find $\sigma_x^{IP} = (100-200)$ μm, $\sigma_y^{IP} \sim 5$ μm, and $\sigma_z^{IP} = (2-3)$ mm. The proper-time difference is calculated from the z positions of the two lepton vertices using Eq. 14.5.1, where $\Delta z = z_1 - z_2$ is the difference between the two z vertices. For OS events, the positively charged lepton is taken as the first lepton (z_1). For SS events Belle uses the absolute value of Δz. *BABAR* applies a beam spot constraint to the two lepton tracks to find the primary vertex of the event in the transverse plane. The positions of closest approach of the two tracks to this vertex in the transverse plane are computed and their z coordinates are denoted z_1 and z_2, where the subscripts refer to the highest and second highest momentum leptons in the $\Upsilon(4S)$ rest frame. The vertex fit constrains the lepton tracks to originate from the same point in the transverse plane, thereby neglecting the nonzero flight length for B^0 mesons. As a consequence, the Δz resolution function is Δz dependent, becoming worse at higher $|\Delta z|$. Neglecting this dependence introduces a small bias that *BABAR* accounts for in the systematic uncertainty.

The signal from the neutral B meson pairs originates either from $B^0\overline{B}^0$ (unm) or from B^0B^0 and $\overline{B}^0\overline{B}^0$ (mix). The signal Δt distributions are expressed by

$$P^{\rm unm}(\Delta t) = N_{\Upsilon(4S)} f_0 b_0^2 \epsilon_{ll}^{\rm unm} \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} (1+\cos(\Delta m_d\Delta t)) \quad (14.5.10)$$

$$P^{\rm mix}(\Delta t) = N_{\Upsilon(4S)} f_0 b_0^2 \epsilon_{ll}^{\rm mix} \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} (1-\cos(\Delta m_d\Delta t)) \quad (14.5.11)$$

where $N_{\Upsilon(4S)}$ is the total number of $\Upsilon(4S)$ events, f_0 and f_+ are the branching fractions of the $\Upsilon(4S)$ to neutral and charged B pairs ($f_0 + f_+ = 1$), b_0 and b_+ are the semileptonic branching fractions for neutral and charged B mesons, ϵ_{ll} with superscript are the efficiencies for selecting dilepton events of charged, unmixed and mixed origins. Belle determines the ratio $\epsilon_{ll}^{\rm chd} : \epsilon_{ll}^{\rm unm} : \epsilon_{ll}^{\rm mix}$ from MC simulation and fixes it in the fit, because detector effects that are not simulated correctly are expected to affect events with these origins equally. The Δz distributions are obtained for these distributions by conversion from Δt and convolution with Δz resolution function.

Belle determines the signal Δz resolution function from J/ψ decays in data, for which the true Δz is equal to zero and whose measured Δz distribution, after the contributions of backgrounds are subtracted, yields the Δz resolution function. A detailed comparison between data and MC simulation shows that after convolving the MC Δz distribution of J/ψ decays with a Gaussian of width $\sigma = (50 \pm 18)\mu$m, the MC distribution agrees with data. They smear the MC background Δt distributions in the same way to account for this discrepancy.

Likelihood fit description (incl. backgrounds)

From di-lepton events *BABAR* measures in a sample of 21 fb^{-1} $\Delta m_d = (0.493 \pm 0.012 \pm 0.009)$ ps^{-1} (Aubert, 2002c) while Belle measures in a sample of 29 fb^{-1} $\Delta m_d = (0.503 \pm 0.008 \pm 0.010)$ ps^{-1} (Hastings, 2003), where the first errors are statistical and the second are systematic. The largest contributions to the systematic errors come from the uncertainties in the B^0 and B^+ lifetimes (~ 0.006 ps^{-1}), in the Δz and in the Δt resolution functions (~ 0.006 ps^{-1}).

Table 25. Measurements of Δm_d. The Δm_d measurements in (Hara, 2002; Tomura, 2002b) have been superseded by (Abe, 2005c) and are not separately included in the B factories average (Asner et al., 2010).

Experiment	Method	$f_{\rm sig.}$	Yield $[B/\mathrm{fb}^{-1}]$	$\int \mathcal{L}\, dt$	Δm_d $[\mathrm{ps}^{-1}]$
BaBar (Aubert, 2002b)	Excl. hadronic modes	86%	214	30 fb^{-1}	$0.516 \pm 0.016 \pm 0.010$
BaBar (Aubert, 2002c)	Incl. di-lepton			21 fb^{-1}	$0.493 \pm 0.012 \pm 0.009$
BaBar (Aubert, 2006l)	$D^*l\nu$ (partial)	64%	605	81 fb^{-1}	$0.511 \pm 0.007 \pm 0.007$
BaBar (Aubert, 2003g)	Excl. $D^*l\nu$	76%	680	21 fb^{-1}	$0.492 \pm 0.018 \pm 0.014$
Belle (Abe, 2001b)	Incl. di-lepton			6 fb^{-1}	$0.463 \pm 0.008 \pm 0.016$
Belle (Hastings, 2003)	Incl. di-lepton			29 fb^{-1}	$0.503 \pm 0.008 \pm 0.010$
Belle (Zheng, 2003)	$D^*\pi$ (partial)			29 fb^{-1}	$0.509 \pm 0.017 \pm 0.020$
Belle (Hara, 2002)	Excl. $D^*l\nu$			29 fb^{-1}	$0.494 \pm 0.012 \pm 0.015$
Belle (Tomura, 2002b)	Excl. hadronic modes			29 fb^{-1}	$0.528 \pm 0.017 \pm 0.011$
Belle (Abe, 2005c)	Excl. hadronic modes, $D^*l\nu$	81%	707	140 fb^{-1}	$0.511 \pm 0.005 \pm 0.006$
B factories average					$0.508 \pm 0.003 \pm 0.003$

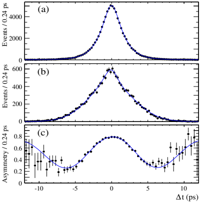

Fig. 64. The Δt distributions for (a) opposite sign and (b) same-sign dilepton events; (c) asymmetry between opposite-sign and same-sign dilepton events. The points are the data and lines correspond to the likelihood fit result (Aubert, 2002c).

Partially-reconstructed final states

BABAR measures Δm_d with a sample of partially-reconstructed $\overline{B}^0 \to D^{*+}l^-\bar{\nu}_l$ events in 81 fb^{-1} (Aubert, 2006l). They select $\overline{B}^0 \to D^{*+}l^-\bar{\nu}_l$ ($l = e$ or μ) events with partial reconstruction of the decay $D^{*+} \to D^0\pi_s^+$, using only the charged lepton from the B^0 decay ($l_{\rm rec}$ and the soft pion (π_s^+) from the D^{*+} decay. This mode has a large selection efficiency since the D^0 decay is not reconstructed and the branching fraction of $\overline{B}^0 \to D^{*+}l^-\bar{\nu}_l$ about half of the semileptonic branching ration of the $\overline{B}^0$. The other B in the event is identified through a second high-momentum lepton $l_{\rm tag}$.

Events are required to have at least four charged tracks. The normalized second Fox-Wolfram moment must be less than 0.5 to reduce background from light quark production in continuum events. The lepton from the B decay must have a momentum in the range 1.3–2.4 GeV/c and the soft pion momentum must be between 60 and 200 MeV/c. By approximating the D^{*+} momentum from the π_s^+ momentum, they calculate the square of the missing neutrino mass $\mathcal{M}_\nu^2$. The $\mathcal{M}_\nu^2$ distribution peaks at zero for signal events, while it is spread over a wide range of negative values for background events.

BABAR determines the $B_{\rm rec}$ decay vertex from a vertex fit of the $l_{\rm rec}^-$ and the π_s^+ tracks, constrained to the beam spot position in the transverse plane, but accounting for the $\overline{B}^0$ flight distance. The decay point of $B_{\rm tag}$ is deter-

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mind from $l^-_{\rm tag}$ and the beam spot similar to the procedure to determine the $B_{\rm rec}$ decay vertex. The flavor of $B_{\rm rec}$ is determined from the lepton and soft pion charges. The flavor of the other B in the event is determined from the charge of $l^-_{\rm tag}$.

After all selection criteria *BABAR* finds 49,000 signal events over a background of 28,000 events in the data sample in the region $\mathcal{M}^2_\nu > -2.5~\mathrm{GeV}^2/c^4$. Backgrounds studies are done with events in the region $\mathcal{M}^2_\nu < -2.5~\mathrm{GeV}^2/c^4$ if no signal candidate is found in the event.

BABAR simultaneously fits the distributions of $\mathcal{M}^2_\nu$, Δt and $\sigma_{\Delta t}$ of the mixed and unmixed events with a binned maximum-likelihood method. Probabilities for a given event to belong to any of the identified background sources ($e^+e^- \to q\overline{q}$ continuum, $B\bar{B}$ combinatorial and B^+ peaking background) are calculated based on the signal and background $\mathcal{M}^2_\nu$ distributions. Signal is considered to be any combination of a lepton and a charged D^{*+} produced in the decay of a single $\overline{B}^0$ meson. They further divide their signal events according to the origin of the tag lepton into primary, cascade, and decay-side lepton tags. A primary lepton tag is produced in the direct decay $B^0 \to Xl^+\bar{\nu}_l$, a cascade lepton tag is produced in the process $B^0 \to DX$, $D \to lY$, and a decay-side tag is produced by the semi-leptonic decay of the unreconstructed D^0. The relative normalization between mixed and unmixed signal events is constrained based on the time-integrated mixing rate χ_d. The Δt signal PDF for both umixed and mixed events consists of the sum of PDFs for primary, cascade, and decay-side tags each convoluted with its own resolution function. They use the standard three Gaussian resolution function with event-by-event Δt uncertainties.

From the fit they get $\tau_{B^0} = (1.504 \pm 0.013^{+0.018}_{-0.013})$ ps and $\Delta m_d = (0.511 \pm 0.007^{+0.007}_{-0.006})~\mathrm{ps}^{-1}$, where the first error is statistical and the second is systematic. The statistical correlation between τ_{B^0} and Δm_d is 0.7%. The results include corrections of -0.006 ps on τ_{B^0} and $+0.007~\mathrm{ps}^{-1}$ on Δm_d due to biases from event selection, boost approximation, B^- peaking background, and combinatorial $B\bar{B}$ background based on MC studies. The systematic error in Δm_d is dominated by uncertainties in the SVT alignment ($^{+0.0038}_{-0.0033}~\mathrm{ps}^{-1}$), the selected range of Δt and $\sigma_{\Delta t}$ ($0.0033~\mathrm{ps}^{-1}$), and the analysis bias ($0.0035~\mathrm{ps}^{-1}$) whereas the largest systematic error sources in the τ_{B^0} measurement are the SVT alignment ($^{+0.0132}_{-0.0038}$ ps), the z scale of the detector (0.0070 ps), and the analysis bias (0.0070 ps).

Belle measures Δm_d with a sample of partially-reconstructed $\overline{B}^0 \to D^{*+}\pi^-$ events in 29.1 fb^{-1} (Zheng, 2003). They select $\overline{B}^0 \to D^{*+}\pi^-_h$ events with partial reconstruction of the decay $D^{*+} \to D^0\pi^+_s$, using only the hard pion (π^-_h) from the $\overline{B}^0$ decay and the soft pion (π^+_s) from the D^{*+} decay. Using this partial reconstruction method, Belle obtains an order of magnitude more events compared to the full reconstruction of the D^{*+}. The flavor of the other B in the event is identified through a high-momentum lepton $l_{\rm tag}$ from semileptonic decay.

Hadronic events are selected by track multiplicty and total energy variables. The hard pion from the B decay must have a momentum in the range 2.05–2.45 GeV/c and the soft pion momentum must be below 450 MeV/c. Belle applies impact parameter requirements on π^-_h and π^+_s to suppress backgrounds from interactions of beam particles with residual gas in the beam pipe or the beam pipe wall. They require both tracks to have SVD information and be not identified as leptons.

The event kinematics are fully constrained by the 4-momentum conservation of the decays $\overline{B}^0 \to D^{*+}\pi^-_h$ and $D^{*+} \to D^0\pi^+_s$, the masses of all particles in these decays, the $\overline{B}^0$ energy and the π^-_h and π^+_s momenta. Belle use two variables, the missing D^0 mass $M_{D_{\rm miss}}$ and the angle between the soft pion in the D^{*+} rest frame and the momentum of the D^{*+} in the center-of-mass frame. The $M_{D_{\rm miss}}$ distribution for signal events peaks sharply at the nominal D^0 mass, while background events spread towards smaller values. Signal events are required to have $M_{D_{\rm miss}} > 1.85$ GeV/c and $0.3 < |\cos\theta^*_{\pi_s}| < 1.05$.

The flavor of $B_{\rm rec}$ is determined from the π^-_h charge. The flavor of the other B in the event is determined from the charge of $l^-_{\rm tag}$. The tag lepton is required to have momentum greater than 1.1 GeV/c and to pass similar requirements on SVD hits and impact parameter as the $B_{\rm rec}$ pions. Leptons that when combined with any other lepton in the event are close to the J/ψ mass are rejected. Belle determines the $B_{\rm rec}$ ($B_{\rm tag}$) decay vertex from the intersection of the π^-_h ($l^-_{\rm tag}$) track with the beam spot accounting for the B meson flight distance.

After all selection criteria Belle finds 3,433 signal events over a background of 1,466 events which are used in the Δm_d measurement. Studies of MC-simulated events show that a significant fraction of the selected events come from $\overline{B}^0 \to D^{*+}\rho^-$ decays.

Belle simultaneously fits the Δt distributions of the mixed and unmixed events with a unbinned maximum-likelihood method. The $B^0\overline{B}^0$ mixing frequency Δm_d is the only free parameter in the fit. The signal Δt resolution function uses a standard triple-Gaussian PDF in the Δt residuals. The resolution function parameters are determined from J/ψ to e^+e^- and $\mu^+\mu^-$ final states. Backgrounds are divided into peaking and non-peaking categories. Non-peaking background is dominated by random combinations of π^-_h and π^+_s with primary leptons from B^0 and $B^\pm$ decays, and combinatorial background from continuum. Peaking background is dominated by the following sources: $\overline{B}^0 \to D^{*+}\pi^-$ and $\overline{B}^0 \to D^{*+}\rho^-$ with secondary-lepton tags or fake lepton tags; $B^0 \to D^{**-}\pi^+$, $B^+ \to \bar{D}^{**0}\pi^+$ and $B^0 \to D^{*-}\pi^+\pi^0$ decays with primary-lepton tags, secondary-lepton tags or fake lepton tags. Peaking and non-peaking background PDFs are convolved with their own resolution functions.

From the fit Belle obtains $\Delta m_d = 0.509 \pm 0.017 \pm 20~\mathrm{ps}^{-1}$, where the first error is statistical and the second is systemtatic. The systematic error in Δm_d is dominated by uncertainties in the background fractions ($0.014~\mathrm{ps}^{-1}$) and the signal Δt resolution function ($0.012~\mathrm{ps}^{-1}$).

Fully-reconstructed final states

BABAR reconstructs neutral B mesons in the decay modes $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $J/\psi K^{*0}$ in a data sample of 20.6 fb^{-1} (Aubert, 2001c, 2002a). Belle uses the B decays to the hadronic final states $D^-\pi^+$, $D^{*-}\pi^+$, and $D^{*-}\rho^+$ in a data sample of 29.2 fb^{-1} (Tomura, 2002b). The decay channels $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, and $K^0_S\pi^+\pi^-$ are used to reconstruct $\overline{D}^0$ candidates, while the modes $K^+\pi^-\pi^+$ and $K^0_S\pi^-$ are used for D^- candidates (Belle does not use the D decay modes involving a K^0_S). Charged D^{*-} candidates are formed by combining a $\overline{D}^0$ with a soft π^-. The B^0 candidates are formed by combining a D^{*-} or D^- with a π^+, ρ^+ ($\rho^+ \to \pi^+\pi^0$) or a_1^+ ($a_1^+ \to \pi^+\pi^-\pi^+$). *BABAR* also reconstructs candidates of $B^0 \to J/\psi K^{*0}$ from combinations of J/ψ candidates, in the decay modes e^+e^- and $\mu^+\mu^-$, with a K^{*0} ($K^{*0} \to K^+\pi^-$). Both experiments reduce background from continuum events by applying requirements on the normalized second Fox-Wolfram moment and the angle between the thrust axis of the particles that form the reconstructed B candidate and the thrust axis of the remaining tracks and unmatched calorimeter clusters in the event, computed in the $\Upsilon(4S)$ frame. Neutral B candidates are identified by their ΔE and $m_{\rm ES}$ values. *BABAR* selects events with $m_{\rm ES} > 5.2$ GeV/c^2 and $|\Delta E|$ within $\pm 2.5\sigma$ of zero. They use the events in the background-dominated region $m_{\rm ES} < 5.27$ GeV/c^2 to determine the background parameters. Belle requires $m_{\rm ES}$ and ΔE to be within $\pm 3\sigma$ around their expected means. They use candidates from a sideband region in the $m_{\rm ES} - \Delta E$ plane to determine the background parameters.

Events with a reconstructed B^0 are then analyzed to determine the flavor of the other B using the B flavor tagging algorithms described in detail in section 5.3. Belle assigns 99.5% of the events to a flavor tag category, while *BABAR* rejects the 30% of events with marginal flavor discrimination.

The decay time difference Δt between B decays is determined from the measured separation $\Delta z = z_{\rm rec} - z_{\rm tag}$ along the z axis between the vertices of the reconstructed $B_{\rm rec}$ and the flavor-tagging $B_{\rm tag}$. The measured Δz is then converted into Δt according to Eq. **??**. *BABAR* applies an event-by-event correction for the directions of the B meson momenta with respect to the z direction in the $\Upsilon(4S)$ frame. Details of the calculation of $z_{\rm rec}$ and $z_{\rm tag}$ and their respective resolutions are given in section 4.

After all selection criteria are applied *BABAR* (Belle) finds 6300 (5300) signal events with an average purity of 86% (80%).

Fit and PDFs

Describe resolution function here, check how much is covered in section 7.

Background events, which are dominated by continuum and $B\bar{B}$ combinatorial sources, are accounted for by additional terms in the PDFs, where the background PDFs provide an empirical description for the possible Δt behavior of the background events. *BABAR* uses separate parameters for each tagging category, while Belle uses a common parameterization. The background types considered are a zero lifetime component and a nonoscillatory component with an empirical nonzero lifetime. Both experiments describe the background resolution function with the same function as the signal resolution function, but with separate parameters to minimize correlations.

BABAR determines the signal probability for each event from fits to the $m_{\rm ES}$ distribution

In fully-reconstructed B decays to hadronic final states *BABAR* measures in a sample of 30 fb^{-1} $\Delta m_d = (0.516 \pm 0.016 \pm 0.010)~\mathrm{ps}^{-1}$ (Aubert, 2001c) where the first error is statistical and the second is systematic. The central value has been corrected by $-0.002 \pm 0.002~\mathrm{ps}^{-1}$ to account for a small variation of the background composition as a function of $m_{\rm ES}$. An additional correction of $-0.007 \pm 0.003~\mathrm{ps}^{-1}$ has been applied to account for a bias observed in fully-simulated MC events due to correlations between the mistag rate and the Δt resolution that are not explicitly included in the likelihood function. The largest contributions to the systematic errors in the *BABAR* measurement come from the uncertainties in the B^0 lifetime ($0.006~\mathrm{ps}^{-1}$) and in the alignment of the SVT ($0.005~\mathrm{ps}^{-1}$). Belle measures in a sample of 29 fb^{-1} $\Delta m_d = (0.528 \pm 0.017 \pm 0.011)~\mathrm{ps}^{-1}$ (Tomura, 2002b).

in the Δz and in the Δt resolution functions (~ 0.006 ps$^-$

Add Belle systematic error.

Event selection ($D^*l\nu$)

Δt measurement

Flavor tagging

Fit and PDFs

Result and dominant systematic errors

Belle performs an analysis combining the exclusive hadro final states $B^0 \to D^{(*)-}\pi^+$, $D^*\rho^+$, $J/\psi K^0_S$, $J/\psi K^{*0}$ with $B^0 \to D^{*-}l\nu$ to measure Δm_d in a sample of 140 fb^{-1} (Abe, 2005c). Dominant systematic errors

The various measurements of Δm_d by the B factories listed in Table 25 have been averaged by the Heavy Flavor Averaging Group (HFAG), where results superseded by more recent ones have been omitted from the average. Before being combined, the Δm_d measurements have been adjusted to a common set of input values, including the B meson lifetimes. The total systematic uncertainity is not negligible; they are dominated by ... Systematic correlations arise from common physics sources (e.g. B lifetimes and branching fractions) and common experimental techniques and algorithms (e.g. flavor tagging, Δt resolution, and background description). Combining the B factories Δm_d measurements and accounting for all identified correlations, HFAG quotes

$$\Delta m_d = (0.508 \pm 0.003 \pm 0.003)~\mathrm{ps}^{-1},$$

where the first error is statistical and the second is systematic. Combining the B factories Δm_d average with time-dependent measurements from the LEP and Tevatron experiments and time-integrated measurements from CLEO and ARGUS gives the same value. The values of Δm_d as measured by different experiments along with the

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- two figures and two tables (one each for lifetimes and mixing)

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