Measurement of B_d^0-$\bar{B}_d^0$ Mixing Rate from the Time Evolution of Dilepton Events at the $\Upsilon(4S)$

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We report a determination of the B_d^0-$\bar{B}_d^0$ mixing parameter Δm_d based on the time evolution of dilepton yields in $\Upsilon(4S)$ decays. The measurement is based on a 5.9 fb^{-1} data sample collected by the Belle detector at KEKB. The proper-time difference distributions for same-sign and opposite-sign dilepton events are simultaneously fitted to an expression containing Δm_d as a free parameter. Using both muons and electrons, we obtain $\Delta m_d = 0.463 \pm 0.008$ (stat) $\pm$ 0.016 (syst) ps^{-1}. This is the first determination of Δm_d from time evolution measurements at the $\Upsilon(4S)$. We also place limits on possible CPT violations.

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The frequency of B_d^0-$\bar{B}_d^0$ mixing is proportional to the mass difference between the two mass eigenstates of the neutral B meson, Δm_d, and is a fundamental parameter of the B system. Measurements of Δm_d derived from the time evolution of B_d^0 decays have been reported by CDF, SLD, and the LEP experiments [1]; ARGUS and CLEO have measured it using the integrated fraction of same-flavor B pair decays in $\Upsilon(4S)$ events [2,3]. We report here the first determination of Δm_d based on the time evolution of B_d^0 decays in $\Upsilon(4S)$ events produced in asymmetric e^+e^- collisions, using data collected by the Belle detector [4] at the KEKB storage ring [5].

At the $\Upsilon(4S)$, the asymmetry in time evolution between same-flavor ($B_d^0 B_d^0$, $\bar{B}_d^0 \bar{B}_d^0$) and opposite-flavor ($B_d^0 \bar{B}_d^0$) decay pairs exhibits an oscillation as a function of the proper-time difference between the two B-meson decays, Δt, with a frequency that is proportional to Δm_d. In KEKB, collisions between 8.0 GeV electrons and 3.5 GeV positrons have a center of mass (c.m.) motion along the electron beam direction (z direction) with a Lorentz boost of $\gamma\beta = 0.425$. Since each of the two B's is produced nearly at rest in the c.m., the separation of their decay vertices in the lab frame is proportional to Δt and has an average magnitude of 200 μm. High-momentum leptons can be used both for tagging the B flavor and for determining the decay vertex with good accuracy. The Δt in dilepton events can thus be used to measure the time evolution of B decays. The same analysis can be used to test CPT conservation by the inclusion of the complex parameter cosθ in the fit [6].

The analysis presented here is based on integrated luminosities of 5.9 fb^{-1} at the $\Upsilon(4S)$ resonance and 0.6 fb^{-1} at an energy that is 60 MeV below the peak.

The Belle detector consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of 1188 aerogel Cerenkov counters (ACC), 128 time-of-flight scintillation counters, and an electromagnetic calorimeter containing 8736 CsI(Tl) crystals (ECL), all located inside the 3.4-m-diameter superconducting solenoid that generates a 1.5 T magnetic field. An iron return yoke, outside the solenoid, is segmented into 14 layers of 4.7-cm-thick iron plates alternating with a system of resistive plate counters that is used to identify muons and K_L mesons (KLM).

Hadronic events are required to have at least five tracks, an event vertex with radial and z coordinates, respectively, within 1.5 and 3.5 cm of the origin, a total reconstructed c.m. energy greater than $0.5W$ [W is the $\Upsilon(4S)$ c.m. energy], a z component of the net reconstructed c.m. momentum less than $0.3W/c$, a total c.m. calorimeter energy between 0.025 and $0.90W$, and a ratio R_2 of the second and zeroth Fox-Wolfram moments [7] that is less than 0.7. While the R_2 cut suppresses events of non-$\Upsilon(4S)$ origin, all other cuts are intended to remove the beam-related background and QED events.

For electron identification, we use position, cluster energy, and shower shape in the ECL, dE/dx in the CDC, and hit information in the ACC. This is ~90% efficient for electrons and has a ~0.3% misidentification probability for charged hadrons with momenta above 1 GeV/c. Electrons from γ conversions are removed.

Muon selection is based on KLM hits associated with charged tracks. The range of the tracks and the matching quality of the hits are used. The efficiency is ~85% for muons with momentum above 1 GeV/c and the misidentification probability is ~2%.

Events containing leptons from J/ψ decays are rejected. In addition, lepton candidates are required to satisfy $30° < \theta < 135°$; $1.1 < p^* < 2.3$ GeV/c; $|dr^{\rm IP}| < 0.05$ cm; $|dz^{\rm IP}| < 2.0$ cm; and have at least one (two) associated SVD hit(s) in the r-ϕ (r-z) view, where θ is the laboratory polar angle, p^* is the c.m. momentum, and $dr^{\rm IP}$ and $dz^{\rm IP}$ are the distances of closest approach to the run-dependent interaction point. To reduce secondary leptons and fakes from the same B and from the continuum, which tend to be back to back, the opening angle $\theta^*_{\ell\ell}$ between the leptons in the c.m. frame is required to satisfy $-0.8 < \cos\theta^*_{\ell\ell} < 0.95$. The application of the above-listed criteria yields 8573 same-sign (SS) and 40 981 opposite-sign (OS) dilepton events on the $\Upsilon(4S)$, and 40 SS and 198 OS dilepton events below the resonance.

The z vertex of leptons is determined from the intersection of the lepton tracks with the profile of B^0_d decay vertices, which is estimated from the profile of the beam interaction point (IP) convolved with the average B flight length [~20 μm in the $\Upsilon(4S)$ rest frame]. The mean position and the width ($\sigma_x^{\rm IP}, \sigma_y^{\rm IP}, \sigma_z^{\rm IP}$) of the IP are determined on a run-by-run basis using hadronic events. We find $\sigma_x^{\rm IP} = 100$–120 μm, $\sigma_y^{\rm IP} \sim 5$ μm, and $\sigma_z^{\rm IP} = 2$–3 mm. The proper-time difference is calculated from the z positions of the two lepton vertices using the relation $\Delta t = \Delta z/c\beta\gamma$, 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 the absolute value of Δz is used.

The observed SS and OS dilepton proper-time distributions have contributions from "signal," defined as events where both leptons are primary leptons from semileptonic decay of B^0_d or B^+, and "background," where at least one lepton is secondary or fake, or the event is from the non-$\Upsilon(4S)$ continuum. The value of Δm_d was extracted by simultaneously fitting the two distributions to the respective sums of contributions from all known signal and background sources.

Each dilepton is identified with one of the event types listed in Table I. Each event type is categorized as either signal (S), correctly tagged background (C), or incorrectly tagged background (W). For each, we parametrize the proper-time distribution as the product of the number of contributing events (N), an overall selection efficiency (ϵ), and a normalized distribution function $\tilde{P}(\Delta t)$. The values of N depend on the total number of $\Upsilon(4S)$ events in the data sample (N_{4S}), the branching fractions of the $\Upsilon(4S)$ to neutral and charged B pairs (f_0 and $f_+ = 1 - f_0$), the semileptonic branching fractions (b_0 and b_+ for neutral and charged B), and, for neutral B's, the mixed event fraction $\chi_d = x_d^2/[2(1 + x_d^2)]$ where $x_d = \tau_{B^0_d}\Delta m_d$ and $\tau_{B^0_d}$ is the B^0_d lifetime. The evaluations of N are summarized in Table I. The efficiencies ϵ are determined by Monte Carlo (MC) simulation.

The observed proper-time distribution function $\tilde{P}(\Delta t)$ for the signal is a convolution of a root distribution with a detector response function, g, and is given by

$$\tilde{P}(\Delta t) = \frac{\int g(\Delta t - \Delta t')F(\Delta t')\, d(\Delta t')}{\iint g(\Delta t - \Delta t')F(\Delta t')\, d(\Delta t')\, d(\Delta t)}, \quad (1)$$

where the respective theoretical root functions for mixed B^0, unmixed B^0, and charged B are

$$F(\Delta t) = (1/4\tau_{B^0_d})e^{-|\Delta t|/\tau_{B^0_d}}[1 - \cos(\Delta m_d \Delta t)], \quad (2)$$

$$F(\Delta t) = (1/4\tau_{B^0_d})e^{-|\Delta t|/\tau_{B^0_d}}[1 + \cos(\Delta m_d \Delta t)], \quad (3)$$

$$F(\Delta t) = (1/2\tau_{B^+})e^{-|\Delta t|/\tau_{B^+}}. \quad (4)$$

MC simulations of generic B^+B^-, unmixed and mixed B^0, and continuum events are used to determine the background Δz distributions. The dominant background source is a primary lepton paired with a secondary lepton from a c quark. The shape as well as the normalization of the background from neutral B events depends on Δm_d. To account for this, we generated two samples of generic

TABLE I. Categorization of event types contributiong to dilepton events.

$\ell\ell$ event type		N	Tag type
SS signal	B^0_d, mixed	$N_{4S}f_0\chi_d b_0^2$	S
SS background	B^0_d, mixed	$N_{4S}f_0\chi_d$	C
	B^0_d, unmixed	$N_{4S}f_0(1 - \chi_d)$	W
	B^+B^-	$N_{4S}f_+$	W
	Continuum	$N_{\rm cont}$	
OS signal	B^0_d, unmixed	$N_{4S}f_0(1 - \chi_d)b_0^2$	S
	B^+B^-	$N_{4S}f_+b_+^2$	S
OS background	B^0_d, mixed	$N_{4S}f_0\chi_d$	W
	B^0_d, unmixed	$N_{4S}f_0(1 - \chi_d)$	C
	B^+B^-	$N_{4S}f_+$	C
	Continuum	$N_{\rm cont}$	

neutral B events, one with $\Delta m_d = 0.464$ ps^{-1} and one with $\Delta m_d = 0.423$ ps^{-1}. Background distributions for arbitrary Δm_d are determined by linear interpolation.

We use the Δz distribution of dileptons from J/ψ decays in the data for g; for these events the root distribution is a delta function and the lepton momentum spectra are in the same region as those of primary leptons from B decays. The Δz distribution for J/ψ events, which has $\sigma = 112$ μm, agrees with the MC distribution if it is convolved with a Gaussian of $\sigma = 50 \pm 18$ μm. This is due to an imperfect detector simulation, and we correct this effect by applying a convolution with $\sigma = 50$ μm to each MC-determined background distribution.

To extract Δm_d, a binned maximum likelihood fit is performed simultaneously to the Δz distributions of the SS and OS dileptons. Each fitting function is a sum of signal and background distributions. In order to properly take into account the tails of the Δz distributions, the signal response function and the background distribution are given in the form of a lookup table rather than an analytic function. We fix the parameters $\tau_{B_d^0} = 1.548$ ps [8], $f_+/f_0 = 1.05$ [9], and $\tau_{B^+}/\tau_{B_d^0} = 1.06$ [8], and limit the fit region to $|\Delta z| < 1.85$ mm. The constraint $b_+/b_0 = \tau_{B^+}/\tau_{B_d^0}$ is imposed. The continuum contribution is fixed to that of off-resonance data, scaled to account for luminosity and energy differences. The relative selection efficiencies for the event types (mixed B_d^0, unmixed B_d^0, and charged B) within each tag type (S, C, and W) are fixed, resulting in two free parameters (efficiency ratios in C/S and W/S) in addition to Δm_d and the overall normalization. The fit result is $\Delta m_d = 0.463 \pm 0.008$ ps^{-1} with χ^2/d.o.f. $= 333/376$. The efficiency ratios in C/S and W/S are $(9.66 \pm 1.39) \times 10^{-3}$ and $(6.98 \pm 0.25) \times 10^{-3}$, respectively, which give signal fractions to be 32.1% (SS) and 77.5% (OS). Figure 1 shows the Δz distributions for the data together with the fitted curves. Figure 2 shows the OS and SS asymmetry, $(N_{\rm OS} - N_{\rm SS})/(N_{\rm OS} + N_{\rm SS})$, for data together with the result of the fit.

As a cross-check, we also measured Δm_d using a fitting method that differs from the one described above in the following aspects [10]: (i) an unbinned rather than binned maximum likelihood fit; (ii) response function is the sum of three Gaussians, with parameters determined from the dileptons from J/ψ decays; (iii) backgrounds separated into SS, OS, rather than C, W; (iv) background distributions were analytic functions, with parameters determined by fitting to MC. We find Δm_d in the range 0.460 to 0.483 ps^{-1} depending on the choice of analytic forms for the backgrounds, which is consistent with the primary result.

The systematic errors were estimated by repeating the fits for different input parameters. The main contribution originates from uncertainties on input parameters and from determination of the response functions. Contributions of f_+/f_0, $\tau_{B_d^0}$, and $\tau_{B^+}/\tau_{B_d^0}$ are estimated by adjusting each in turn by the amount of its uncertainty. Contribution of the response function arises from the possibility that it differs from the true dilepton response function, from the statistical uncertainties of the determination, and from the fact that the calculation of proper time $\Delta t = \Delta z/c\beta\gamma$ is not exact due to the motion of the B's in the c.m. and the energy spread of the beams. To estimate the first possibility, we used the MC dilepton response function convolved with a Gaussian of $\sigma = 50$ μm. For the second, we varied the number of entries on a bin-by-bin basis by the amount of

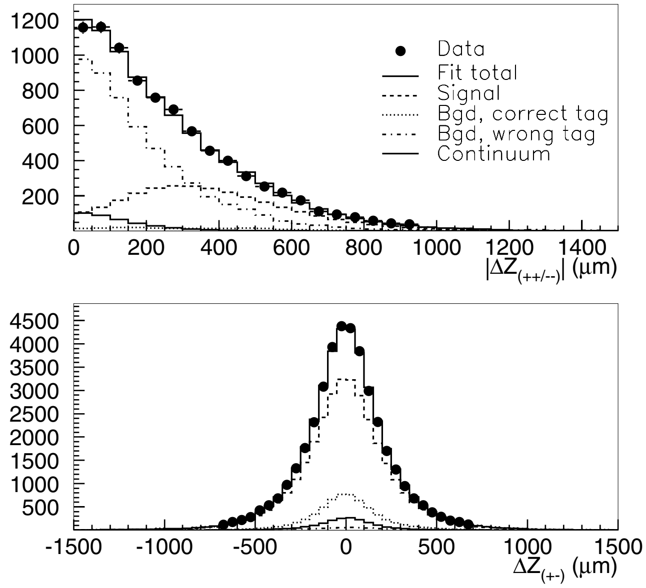

FIG. 1. Δz distribution of dileptons for data together with the fit result. The upper plot shows the distributions for same-sign, and the lower plot for opposite-sign dileptons. Signal and background dileptons obtained from the fit are also shown.

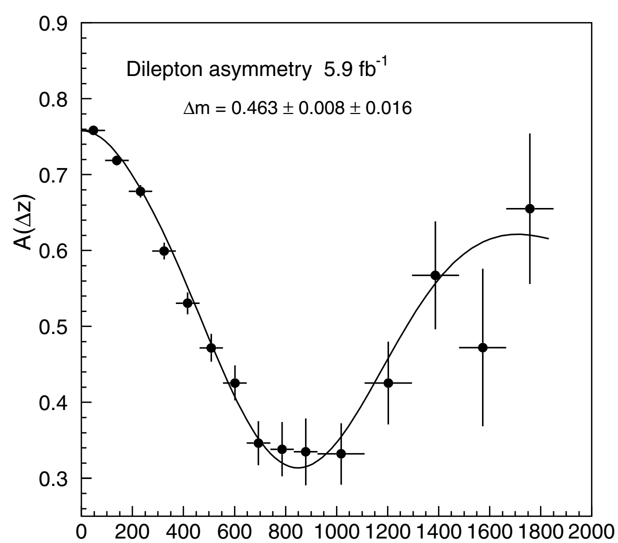

FIG. 2. Opposite-sign and same-sign dilepton asymmetry vs Δz. The asymmetry is defined as $A(\Delta z) = (N_{\rm OS} - N_{\rm SS})/(N_{\rm OS} + N_{\rm SS})$. The points are the data. The curve is the result of the fit.

TABLE II. Summary of systematic errors.

Source (uncertainty)	Δm_d
f_+/f_0 ($\pm$0.08)	$\pm$0.009
B_d^0 lifetime ($\pm$0.032 ps)	$\pm$0.004
$\tau_{B^+}/\tau_{B_d^0}$ ($\pm$0.03)	$\pm$0.009
Response function	$\pm$0.005
Background fake rate ($\pm$35%)	$\pm$0.004
$\mathcal{B}(B \to DX)$ (D^0: $\pm$4.6%, D^+: $\pm$14.3%)	$\pm$0.002
Continuum (SS: $\pm$16%, OS: $\pm$7%)	$\pm$0.002
Detector resolution, Gaussian width ($\pm$18 μm)	$\pm$0.001
Monte Carlo statistics	$\pm$0.004
Total	$\pm$0.016

the statistical errors. For the third, we compared two fits, one using a response function obtained for the true Δt difference and a second obtained for Δz.

We also consider the uncertainty from the background simulation. We assigned a 35% error for the fake rate and adjusted the fake rate by this amount. We varied the branching ratios of B decaying to D^0 and D^+ in the MC in accord with the experimental uncertainties [11]. We varied the width of the Gaussian used to correct for an imperfect detector simulation by ± 18 μm.

It is assumed in the fit that $\Delta\Gamma$, the difference between the decay widths of the neutral B mass eigenstates, is zero. Although no significant experimental constraint exists [3], it is predicted based on solid theoretical grounds to be very small ($\Delta\Gamma/\Gamma < 1\%$) [8]. We repeated the fit including the effects of $\Delta\Gamma/\Gamma = 1\%$ and found the shift in the result to be negligible (<0.001 ps^{-1}).

Contributions to the systematic error from the above sources are summarized in Table II. The total systematic error is obtained by summing all errors in quadrature:

$$\Delta m_d = 0.463 \pm 0.008 \text{ (stat)} \pm 0.016 \text{ (syst) ps}^{-1}.$$

When the constraint of CPT conservation is removed in B_d^0-$\bar{B}_d^0$ mixing, the theoretical functions (2) and (3) are modified and become

$$F(\Delta t) = (|\sin\theta|^2/4\tau_{B_d^0})e^{-|\Delta t|/\tau_{B_d^0}}[1 - \cos(\Delta m_d \Delta t)], \quad (5)$$

$$F(\Delta t) = (1/4\tau_{B_d^0})e^{-|\Delta t|/\tau_{B_d^0}} \times [1 + |\cos\theta|^2 + (1 - |\cos\theta|^2)\cos(\Delta m_d \Delta t) - 2\,\mathrm{Im}(\cos\theta)\sin(\Delta m_d \Delta t)], \quad (6)$$

and χ_d becomes $(|\sin\theta|^2 x_d^2)/[|\sin\theta|^2 x_d^2 + (2 + x_d^2 + x_d^2|\cos\theta|^2)]$. A nonzero value of the complex parameter $\cos\theta$ would be an indication of CPT violation. The result of the fit is [12]

$$\mathrm{Im}(\cos\theta) = 0.035 \pm 0.029 \text{ (stat)} \pm 0.051 \text{ (syst)},$$

$$\mathrm{Re}(\cos\theta) = 0.00 \pm 0.15 \text{ (stat)} \pm 0.06 \text{ (syst)},$$

and $\Delta m_d = 0.461$ ps^{-1}. These results imply [6] the upper limits $|m_{B^0} - m_{\bar{B}^0}|/m_{B^0} < 1.6 \times 10^{-14}$ and $|\Gamma_{B^0} - \Gamma_{\bar{B}^0}|/\Gamma_{B^0} < 0.161$ at the 90% C.L.

In summary, we report the first determination of Δm_d using the time evolution of B^0 mesons produced in $\Upsilon(4S)$ decays. We obtain $\Delta m_d = 0.463 \pm 0.008$ (stat) $\pm$ 0.016 (syst) ps^{-1}, which is consistent with the world average value $\Delta m_d = 0.472 \pm 0.017$ ps^{-1} [8]. We have also examined CPT violation and obtain the first limit on $(m_{B^0} - m_{\bar{B}^0})/m_{B^0}$ and a limit on $(\Gamma_{B^0} - \Gamma_{\bar{B}^0})/\Gamma_{B^0}$ that is compatible with the previous measurement [13].

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