

## Limits on the Decay-Rate Difference of Neutral $B$ Mesons and on $CP$ , $T$ , and $CPT$ Violation in $B^0\bar{B}^0$ Oscillations

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Using events in which one of two neutral  $B$  mesons from the decay of an  $\Upsilon(4S)$  meson is fully reconstructed, we determine parameters governing decay ( $\Delta\Gamma_d/\Gamma_d$ ),  $CP$  and  $T$  violation ( $|q/p|$ ),

and  $CP$  and  $CPT$  violation (Re $z$ , Im $z$ ). The results, obtained from an analysis of 88 million  $\Upsilon(4S)$  decays recorded by *BABAR*, are

$$\begin{aligned} \text{sgn}(\text{Re } \lambda_{CP}) \Delta\Gamma_d/\Gamma_d &= -0.008 \pm 0.037 \text{ (stat.)} \pm 0.018 \text{ (syst.)} \left[ -0.084, 0.068 \right], \\ |q/p| &= 1.029 \pm 0.013 \text{ (stat.)} \pm 0.011 \text{ (syst.)} \left[ 1.001, 1.057 \right], \\ (\text{Re } \lambda_{CP}/|\lambda_{CP}|) \text{Re } z &= 0.014 \pm 0.035 \text{ (stat.)} \pm 0.034 \text{ (syst.)} \left[ -0.072, 0.101 \right], \\ \text{Im } z &= 0.038 \pm 0.029 \text{ (stat.)} \pm 0.025 \text{ (syst.)} \left[ -0.028, 0.104 \right]. \end{aligned}$$

The values inside square brackets indicate the 90% confidence-level intervals. These results are consistent with Standard Model expectations.

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In this Letter, we provide a direct limit on the total decay-rate difference  $\Delta\Gamma_d$  between the  $B_d$  mass eigenstates, and set limits on  $CP$ ,  $T$ , and  $CPT$  violation inherent in the mixing of neutral  $B$  mesons. In the Standard Model  $CPT$  violation is forbidden and the other effects are expected to be non-zero but small, but new physics could provide enhancements [1–3]. We test these predictions by analyzing the time dependence of decays of the  $\Upsilon(4S)$  resonance in which one neutral  $B$  meson ( $B_{\text{rec}}$ ) is fully reconstructed and the other  $B$  ( $B_{\text{tag}}$ ) is identified as being either  $B^0$  or  $\bar{B}^0$ . We reconstruct the flavor states [4]  $B_{\text{flav}} = D^{(*)-} \pi^+ (\rho^+, a_1^+)$  and  $J/\psi K^{*0} (\rightarrow K^+ \pi^-)$  and the  $CP$  eigenstates  $B_{CP} = J/\psi K_s^0, \psi(2S) K_s^0, \chi_{c1} K_s^0$ , and  $J/\psi K_L^0$ . The  $B$  that is not completely reconstructed is “tagged” as being a  $B^0$  or a  $\bar{B}^0$  on the basis of the charges of leptons and kaons, and other indicators of flavor [5]. The data come from 88 million  $\Upsilon(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector [6] at the PEP-II asymmetric-energy  $B$  Factory at SLAC.

The light and heavy  $B_d$  meson mass eigenstates  $B_{L,H}$  are superpositions of  $B^0$  and  $\bar{B}^0$ . This mixing is a consequence of transitions between  $B^0$  and  $\bar{B}^0$  through intermediate states. Oscillations between  $B^0$  and  $\bar{B}^0$  occur with a frequency  $\Delta m_d \equiv m_H - m_L$ . A state that is initially  $B^0$  ( $\bar{B}^0$ ) will develop a  $\bar{B}^0$  ( $B^0$ ) component over time, whose amplitude is proportional to a complex factor denoted  $q/p$  ( $p/q$ ) [7]. Since  $|q/p| \simeq 1$  in the Standard Model, this factor is usually assumed to be a pure phase.

The most general time dependence allowed for the decays of the two neutral  $B$  mesons coming from an  $\Upsilon(4S)$  is [5]

$$\begin{aligned} \frac{dN}{d\Delta t} \propto e^{-\Gamma_d |\Delta t|} &\left[ \frac{|a_+|^2 + |a_-|^2}{2} \cosh\left(\frac{\Delta\Gamma_d \Delta t}{2}\right) + \frac{|a_+|^2 - |a_-|^2}{2} \cos(\Delta m_d \Delta t) - \text{Re}(a_+^* a_-) \sinh\left(\frac{\Delta\Gamma_d \Delta t}{2}\right) \right. \\ &\left. + \text{Im}(a_+^* a_-) \sin(\Delta m_d \Delta t) \right], \quad (1) \end{aligned}$$

where  $\Delta t$  is the difference in proper decay times,  $\Gamma_d$  is the mean decay rate of the two neutral mass eigenstates, and  $\Delta\Gamma_d \equiv \Gamma_H - \Gamma_L$  is their decay-rate difference. The

values of the complex coefficients  $a_{\pm}$  differ for the various combinations of flavor and  $CP$  eigenstates into which the  $B$  mesons decay [5].

In the simplest picture, where  $\Delta\Gamma_d = 0$ , and  $CP$ ,  $T$ , and  $CPT$  violation in mixing are neglected, if the fully reconstructed state is a flavor eigenstate the time distributions with perfect tagging are proportional to  $e^{-\Gamma_d |\Delta t|} (1 \pm \cos(\Delta m_d \Delta t))$ . In practice, the tagging is imperfect and its performance is measured directly from the data. Imperfect tagging reduces the coefficient of  $\cos(\Delta m_d \Delta t)$  by a factor  $1 - 2w$  called the dilution, where  $w$  is the probability of tagging incorrectly.

$B$  decays to a  $CP$  eigenstate  $f_{CP}$  are conveniently parameterized by  $\lambda_{CP} \equiv (q/p) (\bar{\mathcal{A}}_{CP}/\mathcal{A}_{CP})$ , where  $\mathcal{A}_{CP}$  ( $\bar{\mathcal{A}}_{CP}$ ) is the amplitude for  $B^0 \rightarrow f_{CP}$  ( $\bar{B}^0 \rightarrow f_{CP}$ ).  $CP$  violation is characterized by  $\lambda_{CP} \neq \eta_{CP}$  where  $\eta_{CP} = \pm 1$  is the final state’s  $CP$  eigenvalue. The  $CP$  violation observed in decays like  $B \rightarrow J/\psi K_s^0$  [8, 9] involves interference between decays with and without net oscillation, and leads to  $\text{Im } \lambda_{CP} \neq 0$ . Other possible sources of  $CP$  violation are  $|q/p| \neq 1$  and  $|\bar{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| \neq 1$ . We include a test of the former possibility here.

The time distributions for the  $B_{CP}$  samples, in the simplest picture and with perfect tagging, are proportional to

$$e^{-\Gamma_d |\Delta t|} \left[ 1 + |\lambda_{CP}|^2 \pm (1 - |\lambda_{CP}|^2) \cos(\Delta m_d \Delta t) \mp 2 \text{Im } \lambda_{CP} \sin(\Delta m_d \Delta t) \right]. \quad (2)$$

In the Standard Model we have  $\lambda_{CP} = -e^{-2i\beta}$  for  $J/\psi K_s^0$  with the approximation  $\Delta\Gamma_d = 0$ , where  $\beta \equiv \arg[-V_{cd} V_{cb}^*/V_{td} V_{tb}^*]$  is one of the angles of the triangle [10] that represents the unitarity of the quark mixing matrix  $V_{ij}$ . Since  $|\lambda_{CP}| = 1$ , the  $\cos(\Delta m_d \Delta t)$  term is absent. Again, wrongly tagged events reduce the amplitude of the oscillatory terms.

To measure  $\Delta\Gamma_d$ , or  $CP$ ,  $T$ , or  $CPT$  violation in mixing alone we need to find small deviations from these simple patterns. Other effects that can mimic the behavior we seek must be included in the analysis. Among these are asymmetries in the response of the detector to  $B^0$  and  $\bar{B}^0$  decays [5] and interference between dominant

and suppressed decay amplitudes to flavor eigenstates, both those that are fully reconstructed and those that contribute to tagging [5, 11].

The time dependence of the  $B_{CP}$  sample includes a term that is linear in  $\Delta\Gamma_d$ , while the flavor sample has a second-order sensitivity to  $\Delta\Gamma_d$ . Untagged data are included in this analysis and improve our sensitivity to  $\Delta\Gamma_d$  since the contributions of  $\Delta\Gamma_d$ -dependent terms do not depend on whether  $B_{\text{tag}}$  is a  $B^0$  or  $\bar{B}^0$ . With our sample sizes and small measured value of  $\Delta\Gamma_d$ , the  $B_{CP}$  sample dominates our determination of  $\Delta\Gamma_d/\Gamma_d$ . While  $\Delta m_d$  has been well measured previously [12–14], there is only a weak limit,  $|\Delta\Gamma_d/\Gamma_d| < 80\%$  [15], on  $\Delta\Gamma_d$ . A recent theoretical calculation gives  $\Delta\Gamma_d/\Gamma_d = -0.003$  [1].

Violation of  $CP$  and  $T$  in mixing leads to a difference between the  $B^0 \rightarrow \bar{B}^0$  and  $\bar{B}^0 \rightarrow B^0$  oscillation amplitudes proportional to  $|q/p|^4 - 1$ . Our sensitivity to  $|q/p|$  comes mostly from the large flavor-eigenstate sample analyzed. The Standard Model expectation is  $|q/p| - 1 = (2.5 - 6.5) \times 10^{-4}$  [2].

$CPT$  violation in mixing enters the time dependence through the complex quantity

$$z \equiv 2 \frac{\delta m_d - \frac{i}{2} \delta \Gamma_d}{\Delta m_d - \frac{i}{2} \Delta \Gamma_d}, \quad (3)$$

where  $\delta m_d$  ( $\delta \Gamma_d$ ) is the  $B^0 - \bar{B}^0$  difference of effective mass (decay rate) expectation values for the  $B^0$  and  $\bar{B}^0$  flavor eigenstates. A non-zero value of either  $\delta m_d$  or  $\delta \Gamma_d$  is only possible if both  $CP$  and  $CPT$  are violated. The dominant contribution of  $\text{Im} z$  to the time dependence is through the coefficient of  $\sin(\Delta m_d \Delta t)$  for flavor eigenstates, while  $\text{Re} z$  contributes primarily to the coefficients of  $\cosh(\Delta \Gamma_d \Delta t / 2) \approx 1$  and  $\cos(\Delta m_d \Delta t)$  for  $CP$  eigenstates. The measurement of  $z$  presented here is more general than previous analyses based on  $B$  decays [13, 16] and complements earlier limits on the  $K^0 - \bar{K}^0$  mass difference  $\delta m_K / m_K < 10^{-18}$  [7].

Interference effects between the amplitudes for dominant decays of flavor eigenstates (e.g.,  $B^0 \rightarrow D^- \pi^+$ ) and for doubly-CKM-suppressed (DCS) decays (e.g.,  $\bar{B}^0 \rightarrow D^- \pi^+$ ) are analogous to the interference familiar in decays to  $CP$  eigenstates [11]. They thus affect, in particular, the  $\sin(\Delta m_d \Delta t)$  terms and have the potential to obscure a similar contribution from  $\text{Im} z$ . The size of the DCS interference relative to the dominant decay is governed by  $\lambda_{\text{flav}}$ , defined analogously to  $\lambda_{CP}$ , and we expect  $|\lambda_{\text{flav}}| \approx |q/p| |V_{ub} V_{cd}^* / V_{cb}^* V_{ud}| \simeq 0.02 |q/p|$ . There are similar interference contributions from DCS amplitudes for  $B^0$  decays to states  $f_{\text{flav}}$  of opposite flavor and from DCS amplitudes in the  $B_{\text{tag}}$  decay. We write  $\bar{\lambda}_{\text{flav}} = 1/\lambda_{\text{flav}}$  so  $|\bar{\lambda}_{\text{flav}}| \approx 0.02 |p/q|$ . We can represent the cumulative effect of all such decays with four complex numbers,  $\lambda_{\text{flav}}$ ,  $\bar{\lambda}_{\text{flav}}$ ,  $\lambda_{\text{tag}}$ , and  $\bar{\lambda}_{\text{tag}}$  [17].

We combine all the data for the  $CP$  eigenstates, taking into account the  $CP$  eigenvalue of the final state. We assume  $|\bar{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| = 1$  (but vary this ratio as a systematic

study) as expected theoretically at the  $10^{-3}$  level [18] and as supported by the average of  $B$ -Factory measurements of states of charmonium and  $K_S^0$  or  $K_L^0$ , for which we found  $|\bar{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| = 0.949 \pm 0.045$  [8, 9], when  $\Delta\Gamma_d = 0$  and  $|q/p| = 1$  are assumed.

The time interval  $\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$  between the two  $B$  decays is calculated from the measured separation  $\Delta z$  between the decay vertices of  $B_{\text{rec}}$  and  $B_{\text{tag}}$  along the collision axis [8]. We determine the position of the  $B_{\text{rec}}$  vertex from its charged tracks. The  $B_{\text{tag}}$  decay vertex is determined by fitting to a common vertex tracks not belonging to the  $B_{\text{rec}}$  candidate, employing constraints from the beam spot location and the  $B_{\text{rec}}$  momentum [8]. The r.m.s.  $\Delta t$  resolution for 99.7% of the events used is 1.0 ps.

Resolution effects for signal events are modeled by convolving the idealized decay rate with a sum of three Gaussian distributions, two of whose widths and biases are scaled with each event's estimated  $\Delta t$  uncertainty  $\sigma_{\Delta t}$ .

We use four mutually-exclusive categories to assign tags, based on kinematic, particle type, and charge information [8]. There are separate reconstruction efficiencies and mistag probabilities for  $B^0$  and  $\bar{B}^0$  tags, to accommodate differences in detector response to  $B^0$  and  $\bar{B}^0$  decays. In addition, we introduce a linear dependence of the mistag probability on  $\sigma_{\Delta t}$ , except for events tagged with a high-momentum lepton.

Backgrounds are primarily due to misreconstructed  $B_{\text{rec}}$  candidates and are studied in data using mass or energy sidebands. Events are assigned signal and background probabilities based on their proximity to the signal peak. We model backgrounds with empirical  $\Delta t$  distributions that can accommodate contributions from decays with a range of lifetimes.

The parameters of primary interest in this analysis are  $\text{sgn}(\text{Re} \lambda_{CP}) \Delta\Gamma_d/\Gamma_d$ ,  $|q/p|$ ,  $(\text{Re} \lambda_{CP}/|\lambda_{CP}|) \text{Re} z$ , and  $\text{Im} z$ . We cannot determine  $\Delta\Gamma_d/\Gamma_d$  and  $\text{Re} z$  directly because both occur multiplied by  $\text{Re} \lambda_{CP}$  in their dominant contributions to the decay rate. They are thus subject to a sign ambiguity, which can be resolved by relying on additional information from the unitarity triangle. The average lifetime  $\tau_{B^0} \equiv 1/\Gamma_d$  is fixed at 1.542 ps [7]. The parameters  $\Delta m_d$  and  $\text{Im} \lambda_{CP}/|\lambda_{CP}|$  are determined together with the main parameters as cross checks against earlier measurements [8, 12]. The terms proportional to the real parts of the DCS parameters  $\lambda_{\text{flav}}$ ,  $\bar{\lambda}_{\text{flav}}$ ,  $\lambda_{\text{tag}}$ ,  $\bar{\lambda}_{\text{tag}}$  are small and therefore neglected in the nominal fit model. For each of the four parameters  $\lambda$ s,  $\text{Im} \lambda/|\lambda|$  and  $|\lambda|$  are treated as independent variables. For all sets of nonleptonic flavor eigenstates analyzed, the magnitude of each  $|\lambda|$  is fixed to 0.02 (up to a factor  $|q/p|$  or  $|p/q|$ ) but  $\text{Im} \lambda/|\lambda|$  is left unconstrained. The decay model uses 26 more parameters to model the effects of experimental  $\Delta t$  resolution (10),  $B^0/\bar{B}^0$  tagging capability (11), and reconstruction and tagging efficiencies (5). An additional 22 parameters model the levels and

TABLE I: Fit results allowing ( $z$  free) or not allowing ( $z = 0$ )  $CPT$  violation in  $B^0\bar{B}^0$  oscillations.

Parameter	$z$ Free	$z = 0$
$\text{sgn}(\text{Re } \lambda_{CP}) \Delta\Gamma_d/\Gamma_d$	$-0.008 \pm 0.037$	$-0.009 \pm 0.037$
$ q/p $	$1.029 \pm 0.013$	$1.029 \pm 0.013$
$(\text{Re } \lambda_{CP}/ \lambda_{CP} ) \text{Re } z$	$0.014 \pm 0.035$	—
$\text{Im } z$	$0.038 \pm 0.029$	—

$\Delta t$  dependence of backgrounds. A total of 58 free parameters are determined with a simultaneous unbinned maximum-likelihood fit to the  $\Delta t$  distributions of  $CP$  and flavor-eigenstate samples [5].

Table I summarizes the results of fits allowing ( $z$  free) or not allowing ( $z = 0$ )  $CPT$  violation in  $B^0\bar{B}^0$  oscillations. The largest statistical correlations involving the parameters of interest are between  $|q/p|$  and parameters modeling  $B^0\bar{B}^0$  asymmetries in reconstruction efficiency and mistag probabilities, and between  $\text{Im } z$  and the DCS contributions to  $B_{\text{tag}}$  decay amplitudes. The fitted values of  $\Delta m_d$  and  $\text{Im } \lambda_{CP}/|\lambda_{CP}|$  are consistent with recent  $B$ -Factory measurements [8, 9, 12, 14]. When  $z$  is fixed, the value of  $\text{Im } \lambda_{CP}/|\lambda_{CP}|$  decreases by 0.011 with unchanged statistical uncertainty, while the value and uncertainty on  $\Delta m_d$  is unchanged. No statistically significant  $B^0\bar{B}^0$  differences in reconstruction and tagging efficiencies are observed.

We have used data and Monte Carlo samples to validate our analysis technique. Tests with large, parameterized Monte Carlo samples demonstrate that the observed statistical uncertainties and correlations are consistent with expectations. Analyses of Monte Carlo samples generated with a detailed detector simulation verify that the analysis procedure is unbiased. Fits to data subsamples selected by tagging category, running period, and  $B_{\text{rec}}$  decay mode give consistent results. Changes to the algorithms used to estimate  $\Delta t$  and  $\sigma_{\Delta t}$  or to their allowed ranges also have no statistically significant effect. Fits to samples of charged  $B$  decays in which no oscillations are present give the expected results.

We identify four general sources of systematic uncertainty with the contributions shown in Table II for the fit in which  $z$  is free [5]. The first is possible bias in the event selection and fit method: we see no evidence of such bias when analyzing Monte Carlo samples and assign the statistical uncertainty of these checks as a systematic uncertainty on the final results. The second is the  $\Delta t$  measurement. The choice of parameterization of the resolution function dominates this uncertainty, but assumptions about the beam spot and detector alignment contribute as well. Assumptions about the properties of signal  $\Upsilon(4S) \rightarrow B_{\text{rec}}B_{\text{tag}}$  decays include the values of the lifetime,  $|\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP}|$ , and DCS parameters, and are the third source of systematic uncertainty. Uncertainties in the size and  $\Delta t$  distributions of background events (BG)

TABLE II: Summary of systematic uncertainties ( $z$  free).

Source	$\text{sgn}(\text{Re } \lambda_{CP})$		$\text{Re } \lambda_{CP}/ \lambda_{CP} $	
	$\times \Delta\Gamma_d/\Gamma_d$	$ q/p $	$\times \text{Re } z$	$\text{Im } z$
Analysis Method	0.006	0.007	0.005	0.016
$\Delta t$ Resolution	0.013	0.003	0.008	0.016
Signal Properties	0.010	0.008	0.033	0.009
BG Properties	0.005	0.003	0.007	0.004
Total	0.018	0.011	0.034	0.025

incorrectly identified as  $\Upsilon(4S) \rightarrow B_{\text{rec}}B_{\text{tag}}$  make small contributions to the systematic uncertainties.

Different sources dominate the systematic uncertainty for each parameter. Most systematic uncertainties are determined with data and will decrease with additional statistics. The largest single source of uncertainty is the contribution of the DCS parameters to  $(\text{Re } \lambda_{CP}/|\lambda_{CP}|) \text{Re } z$  and it is estimated by varying the DCS phase parameters over their full allowed range, and  $|\overline{\mathcal{A}}_{\text{flav}}/\mathcal{A}_{\text{flav}}|$  and  $|\overline{\mathcal{A}}_{\text{flav}}/\overline{\mathcal{A}}_{\text{flav}}|$  over the range 0–0.04. Systematic uncertainties on  $\text{sgn}(\text{Re } \lambda_{CP}) \Delta\Gamma_d/\Gamma_d$  and  $|q/p|$  for the analysis assuming  $z = 0$  were evaluated similarly as  $\pm 0.020$  and  $\pm 0.012$ , respectively.

Using the world-average value of  $\Delta m_d$  [7], we derive the value  $\text{sgn}(\text{Re } \lambda_{CP}) \Delta\Gamma_d/\Delta m_d = -0.011 \pm 0.049(\text{stat.}) \pm 0.024(\text{syst.})$ , corresponding to the range  $[-0.116, 0.091]$  at the 90% confidence level, from the fit results with  $z$  free. The limit on  $CP$  and  $T$  violation in oscillations is independent of and consistent with our previous measurement based on an analysis of inclusive dilepton events [19]. Using Eq. (3) and taking the world-average  $B_d$  mass [7], we derive  $|\delta m_d|/m_{B_d} < 1.0 \times 10^{-14}$  and  $-0.156 < \delta\Gamma_d/\Gamma_d < 0.042$  at the 90% confidence level. Figure 1 shows the results of the fit with  $z$  free in the  $(|q/p| - 1, |z|)$  plane, compared to the previous  $BABAR$  measurement of  $|q/p|$ , and to Standard Model expectations.

Conventional analyses of oscillations and  $CP$  violation in the  $B_d$  system neglect possible contributions from several sources that are expected to be small in the Standard Model. This analysis includes these effects and finds results consistent with Standard Model expectations. While the Standard Model predictions for  $\Delta\Gamma_d$ ,  $|q/p|$ , and  $z$  are well below our current sensitivity, higher-precision measurements may still bring surprises.

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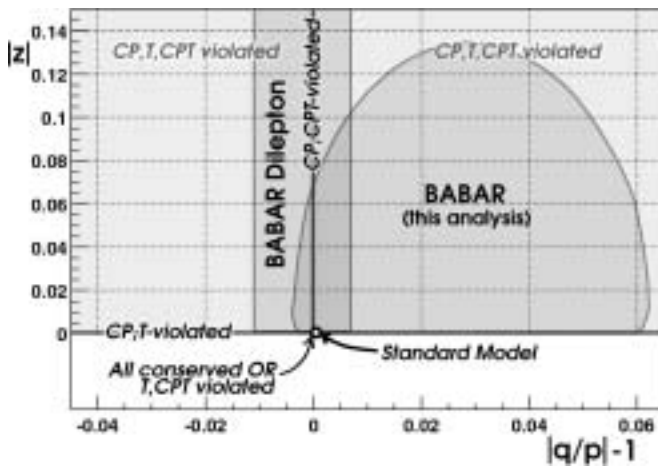


FIG. 1: Favored regions at 68% confidence level in the  $(|q/p|-1, |z|)$  plane determined by this analysis and by the *BABAR* measurement of the dilepton asymmetry [19]. Labels reflect the requirements that both  $CP$  and  $T$  be violated if  $|q/p| \neq 1$  and that both  $CP$  and  $CPT$  be violated if  $|z| \neq 0$ . The dilepton measurement constrains  $|q/p|$  without assumptions on the value of  $|z|$ . The Standard Model expectation of  $|q/p|-1 = (2.5 - 6.5) \times 10^{-4}$  is obtained from Ref. [2].

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