March 2008

BABAR-PROC-07/115
SLAC-PUB-13159

Search for CPT Violation in B^0-$\overline{B}^0$ Oscillations with BaBar*

D.P. STOKER (for the *BABAR* Collaboration)

Department of Physics and Astronomy,
University of California at Irvine,
Irvine, CA 92697, USA
E-mail: dpstoker@uci.edu

I describe searches for CPT violation in B^0-$\overline{B}^0$ oscillations using $\Upsilon(4S) \to B\overline{B}$ decays recorded by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. Preliminary results are given for combinations of the quantities Δa_μ in the Lorentz-violating standard-model extension.

INTRODUCTION

In the general Lorentz-violating standard-model extension (SME) [1], the parameter for CPT violation in neutral meson oscillations depends on the 4-velocity of the meson [2]. We have searched [3] for this effect using $\Upsilon(4S) \to B\overline{B}$ decays recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. Any observed CPT asymmetry should vary with a period of one sidereal day ($\simeq 0.99727$ solar-day) as the $\Upsilon(4S)$ boost direction follows the Earth's rotation with respect to the distant stars [4].

The "light" and "heavy" physical states of the B^0-$\overline{B}^0$ system are

$$\begin{aligned} |B_L\rangle &= p\sqrt{1-\mathsf{z}}|B^0\rangle + q\sqrt{1+\mathsf{z}}|\overline{B}^0\rangle, \\ |B_H\rangle &= p\sqrt{1+\mathsf{z}}|B^0\rangle - q\sqrt{1-\mathsf{z}}|\overline{B}^0\rangle. \end{aligned} \tag{1}$$

The complex parameter z vanishes if CPT is conserved; T invariance implies $|q/p| = 1$. In the $w\xi$ formalism of the SME, $\xi = -\mathsf{z}$ and $w = |q/p|$.

In the SME, flavor-dependent Lorentz and CPT-violating coupling coefficients for the two valence quarks in the B^0 meson are contained in quantities Δa_μ. The CPT parameter z depends on the meson 4-velocity $\beta^\mu = \gamma(1, \vec{\beta})$ in the observer frame as [2]

$$\mathsf{z} \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}, \tag{2}$$

where $\beta^\mu \Delta a_\mu$ is real and varies with sidereal time due to the rotation of $\vec{\beta}$ relative to the constant vector $\Delta\vec{a}$. The magnitude of the decay rate difference $\Delta\Gamma \equiv \Gamma_H - \Gamma_L$ is known to be small compared to the B^0-$\overline{B}^0$ oscillation frequency $\Delta m \equiv m_H - m_L$; hence the SME constrains

$$\Delta m \mathrm{Re}\,\mathsf{z} \simeq 2\Delta m(\Delta m/\Delta\Gamma)\mathrm{Im}\,\mathsf{z} \simeq \beta^\mu \Delta a_\mu. \tag{3}$$

Analogous Δa_μ apply to oscillations of other neutral mesons. Limits on Δa_μ specific to $K^0\overline{K}^0$ oscillations [5] and to $D^0\overline{D}^0$ oscillations [6] have been reported by the KTeV and FOCUS collaborations, respectively. KTeV has also reported constraints on sidereal variation of the CPT parameter ϕ_{+-} [7].

We adopt [8] the basis $(\hat{X}, \hat{Y}, \hat{Z})$ for the fixed frame containing $\Delta\vec{a}$ and the basis $(\hat{x}, \hat{y}, \hat{z})$ for the rotating laboratory frame. We take β^μ for each B meson to be the $\Upsilon(4S)$ 4-velocity and choose $\hat{z}$ to lie along $-\vec{\beta}$, so that

$$\beta^\mu \Delta a_\mu = \gamma\left[\Delta a_0 - \beta\Delta a_Z \cos\chi - \beta \sin\chi\left(\Delta a_Y \sin\Omega\hat{t} + \Delta a_X \cos\Omega\hat{t}\right)\right] \tag{4}$$

where the sidereal time $\hat{t}$ is given by the right ascension of $\hat{z}$ as it precesses around the Earth's rotation axis ($\hat{Z}$) at the sidereal frequency Ω. The latitude (37.4° N) and longitude (122.2° W) of *BABAR* and the $\Upsilon(4S)$ Lorentz boost ($\langle\beta\gamma\rangle \simeq 0.55$ toward 37.8° east of south) yield $\hat{t} = 14.0$ sidereal-hours at the Unix epoch (00:00:00, 1 Jan. 1970) and $\cos\chi = \hat{z}\cdot\hat{Z} = 0.628$.

---

* Presented at the *Fourth Meeting on CPT and Lorentz Symmetry*, Indiana University, Bloomington (August 8–11, 2007).

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

SEARCH USING INCLUSIVE DILEPTON EVENTS

Neutral B mesons from $\Upsilon(4S)$ decay evolve in orthogonal flavor states until one decays, after which the flavor of the other continues to oscillate. We use *direct* semileptonic decays (where $b \to X\ell\nu$, with $\ell = e$ or μ) to tag the flavor of each $B^0(\overline{B}^0)$ by the charge of its daughter lepton $\ell^+(\ell^-)$. To first order in z, the decay rate for opposite-sign dilepton ($\ell^+\ell^-$) events is

$$N^{+-} \propto e^{-|\Delta t|/\tau_{B^0}} \quad \begin{array}{l}\{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m \Delta t) \\ -2\,\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta t/2) + 2\,\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)\}.\end{array} \tag{5}$$

We define $\Delta t \equiv t^+ - t^-$ to be the difference of the proper times for B meson decays to ℓ^+, ℓ^-. The asymmetry A_{CPT} between the decay rates at $\Delta t > 0$ and $\Delta t < 0$ compares the probabilities $P(B^0 \to B^0)$ and $P(\overline{B}^0 \to \overline{B}^0)$:

$$A_{CPT}(\Delta t) \simeq \frac{-\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma\Delta t + 2\,\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)}{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)}. \tag{6}$$

Here we make the approximation $\sinh(\Delta\Gamma\Delta t/2) \simeq \Delta\Gamma\Delta t/2$, which is valid for the range $|\Delta t| < 15\,\mathrm{ps}$ used in this analysis. We use $|\Delta\Gamma| = 6\times 10^{-3}\,\mathrm{ps}^{-1}$ in the $\cosh(\Delta\Gamma\Delta t/2)$ term, consistent with the central value in Ref. [9].

The *BABAR* detector is described in detail elsewhere [10]. Any day/night variations in detector response tend to cancel over sidereal time for long data-taking periods. We use about 232 million $\Upsilon(4S) \to B\overline{B}$ decays and $16\,\mathrm{fb}^{-1}$ of off-resonance data, from 40 MeV below the $\Upsilon(4S)$ resonance, collected during 1999–2004 to search for variations in z of the form

$$\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1\cos(\Omega t + \phi). \tag{7}$$

Each event's timestamp yields the time elapsed since the Unix epoch. We use this time, folded over one sidereal day, for t in Eq. 7.

The event selection is the same as in Ref. [11]. Briefly, we suppress non-$B\overline{B}$ background by event-shape and event-topology requirements, and select events having at least two well-identified lepton candidates with momenta $0.8-2.3\,\mathrm{GeV}/c$ in the $\Upsilon(4S)$ rest frame that are not part of reconstructed $J/\psi, \psi(2S) \to e^+e^-, \mu^+\mu^-$ decays or photon conversions. Lepton candidates must have at least one z-coordinate measurement in the silicon vertex tracker (SVT) to allow Δt to be well-measured. We reject events for which a neural-network algorithm classifies either of the two highest-momentum lepton candidates (the *dilepton*) as a *cascade* lepton from a $b \to (c,\tau) \to \ell$ transition. The selected dilepton sample comprises 1.18 million opposite-sign events and 0.22 million same-sign events.

To measure Δt, we assume each lepton originates from a direct B meson decay at the point on the lepton track with the least transverse distance to the $\Upsilon(4S)$. The component Δz, along the Lorentz boost, of the distance between these two points yields $\Delta t = \Delta z/\langle\beta\gamma\rangle c$. For opposite-sign events $\Delta z = z^+ - z^-$; for same-sign events we take $\Delta z > 0$.

We model the Δt-distribution of the dilepton sample with the probability density functions (PDFs) used in Ref. [11] to represent contributions from $B^0\overline{B}^0$ and B^+B^- decays and non-$B\overline{B}$ events. The latter are estimated, using off-resonance data, to be 3.1% of the sample. The fit to data determines that 59% of the $B\overline{B}$ events are B^+B^- decays. With contributions of minor $B\overline{B}$ backgrounds fixed to values from Monte Carlo (MC) simulation, the fit to data determines the fractions of $B^0\overline{B}^0$ and B^+B^- decays that are *signal* events ($\simeq 80\%$) with two direct leptons, and the fractions that are *opposite B cascade* (*obc*) events with one direct lepton and a $b \to c \to \ell$ decay of the other B meson ($\simeq 10\%$). Same-sign dilepton events are retained to improve the determination of the *signal* and *obc* fractions.

Each PDF is a convolution of a decay rate in Δt with a resolution function that is a sum of Gaussians or, for events with a cascade lepton, its convolution with one or two double-sided exponentials accounting for the lifetimes of intermediate τ or $D_{(s)}$ meson states, respectively. For signal events, the resolution function is determined by the fit to data, with the width of the third (widest) Gaussian fixed at 8 ps. For leptons from different B mesons, we use a $B^0\overline{B}^0$ decay rate that contains z (Eq. 5) for opposite-sign events and is $\propto e^{-|\Delta t|/\tau_{B^0}}\{\cosh(\Delta\Gamma\Delta t/2) - \cos(\Delta m\Delta t)\}$ for same-sign events; for B^+B^- decays, it is $\propto e^{-|\Delta t|/\tau_{B^\pm}}$. For leptons from the same B meson, the decay rates are exponentials with effective lifetimes determined from MC simulation. Dilution factors are included to account for wrong flavor tags in non-signal events.

We extract z from a maximum likelihood fit to the numbers of opposite-sign and same-sign dilepton events, each binned in Δt and sidereal time t.

Several sources of systematic uncertainty are considered. We vary separately τ_{B^0}, $\tau_{B^\pm}$, and Δm by their known uncertainties [12], and $|\Delta\Gamma|$ over the range $0-0.1\,\mathrm{ps}^{-1}$. Fixed parameters in the PDF resolution functions for non-signal events are varied separately by 10%, as are fixed $B\overline{B}$ background component fractions. The effects of possible

SVT internal misalignments and uncertainty in the absolute z-scale are evaluated in $B^0\overline{B}^0$ MC samples. We use $e^+e^- \to \mu^+\mu^-(\gamma)$ data events, with true $\Delta z = 0$, to check for sidereal variations in measured Δz that could mimic a Lorentz-violation signal and find a negligibly small amplitude of $(0.022 \pm 0.025)\,\mu$m.

Our preliminary results for the CPT violation parameter in Eq. 7 are:

$$\begin{aligned}
\mathrm{Im}\,\mathsf{z}_0 &= (-14.1 \pm 7.3(\mathrm{stat.}) \pm 2.4(\mathrm{syst.})) \times 10^{-3}, \\
\mathrm{Re}\,\mathsf{z}_0\,\Delta\Gamma &= (-7.2 \pm 4.1(\mathrm{stat.}) \pm 2.1(\mathrm{syst.})) \times 10^{-3}\mathrm{ps}^{-1}, \\
\mathrm{Im}\,\mathsf{z}_1 &= (-24.0 \pm 10.7(\mathrm{stat.}) \pm 5.9(\mathrm{syst.})) \times 10^{-3}, \\
\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma &= (-18.8 \pm 5.5(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-3}\mathrm{ps}^{-1}.
\end{aligned} \tag{8}$$

The statistical correlation between $\mathrm{Im}\,\mathsf{z}_0$ and $\mathrm{Re}\,\mathsf{z}_0\,\Delta\Gamma$ is 76%; between $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$ it is 79%. We note that $\mathsf{z} \to -\mathsf{z}$ for $\phi \to \phi + \pi$ in Eq. 7. The results are compatible with the SME constraint $\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma \simeq 2\Delta m\,\mathrm{Im}\,\mathsf{z}$.

In Fig. 1 we exhibit the sidereal-time dependence of the measured asymmetry A_{CPT}^{meas} for the opposite-sign dilepton events with $|\Delta t| > 3\,$ps, thereby omitting highly-populated bins where any asymmetry is predicted to be small. Figure 2 shows confidence level contours for $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$. The significance for sidereal variations in z is 2.2σ.

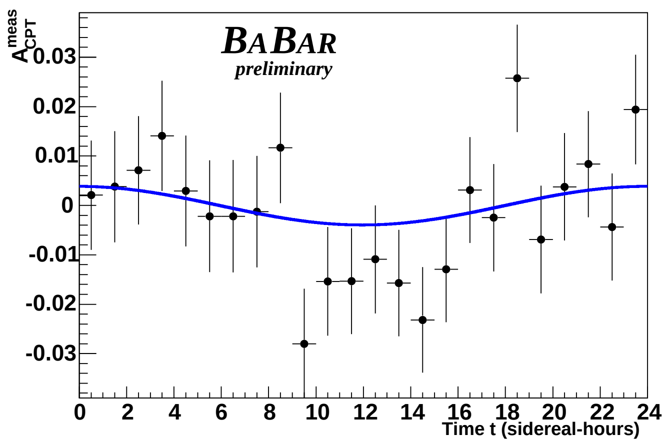

FIG. 1: Asymmetry A_{CPT}^{meas} for opposite-sign dilepton events with $|\Delta t| > 3\,$ps versus sidereal time ($t = 0$ at Unix epoch). The curve is a projection, for $|\Delta t| > 3\,$ps, using results of the two-dimensional likelihood fit for $|\Delta t| < 15\,$ps.

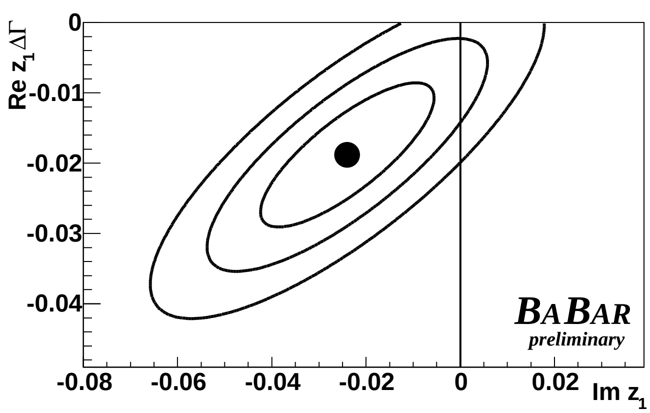

FIG. 2: Contours showing 1σ, 2σ, and 3σ significance for $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$.

We use Eqs. 3, 4, and 8 to extract values for the SME quantities Δa_μ:

$$\begin{aligned}
\Delta a_0 - 0.30\Delta a_Z &\approx -(5.2 \pm 4.0)(\Delta m/\Delta\Gamma) \times 10^{-15}\,\mathrm{GeV}, \\
\sqrt{(\Delta a_X)^2 + (\Delta a_Y)^2} &\approx (37 \pm 16)|\Delta m/\Delta\Gamma| \times 10^{-15}\,\mathrm{GeV}.
\end{aligned}$$

We now use the periodogram method [13] to compare the spectral power for variations in z at the sidereal frequency with those in a wide band of surrounding frequencies. The spectral power at a test frequency ν is

$$P(\nu) \equiv \frac{1}{N\sigma_w^2}\left|\sum_{j=1}^{N} w_j e^{2i\pi\nu T_j}\right|^2, \tag{9}$$

where N data points measured at times T_j have weights w_j with variance σ_w^2. Here, T_j is the time elapsed since the Unix epoch for opposite-sign dilepton event j. We use weights $w_j \propto \Delta m\Delta t_j - \sin(\Delta m\Delta t_j)$, obtained by applying the SME constraint $\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma \simeq 2\Delta m\,\mathrm{Im}\,\mathsf{z}$ to the numerator of Eq. 6. In the absence of an oscillatory signal, the probability that $P(\nu)$ exceeds a value S at a preselected frequency is $\exp(-S)$; if M independent frequencies are tested, the largest $P(\nu)$ value exceeds S with probability

$$\Pr\left\{P_{\max}(\nu) > S; M\right\} = 1 - \left(1 - e^{-S}\right)^M. \tag{10}$$

We use 20994 test frequencies from 0.26 year^{-1} to 2.1 solar-day^{-1}, separated by 10^{-4} solar-day^{-1}. This oversamples the frequency range by a factor of about 2.2 and avoids underestimating the spectral power of a signal. The number of independent frequencies is about 9500.

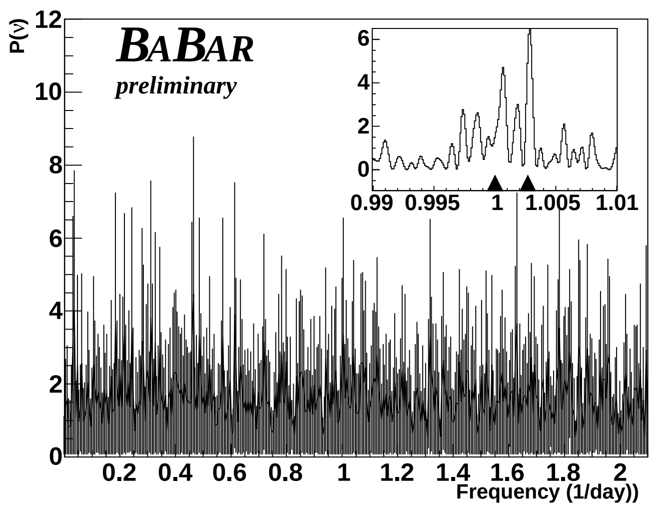

FIG. 3: Periodogram for opposite-sign dilepton events. The solar-day and sidereal-day frequencies are marked by triangles in the inset.

Figure 3 shows the largest spectral power we obtain is $P_{\max}(\nu) = 8.80$. With no signal, a larger value is expected with 76% probability. At the sidereal frequency, $P(\nu) = 5.28$ — a value exceeded at 78 test frequencies. The inset of Fig. 3 shows the sidereal frequency lies 1.6 bin-widths below a peak with $P(\nu) = 6.57$. At the solar-day frequency, where any effects due to day/night variations in detector response should appear, $P(\nu) = 1.47$.

Neither the likelihood fit nor the periodogram method detect asymmetries large enough to provide strong evidence for CPT and Lorentz violation.

SEARCH USING RECONSTRUCTED CP AND FLAVOR EIGENSTATES

A previous search [9] for CPT violation yielded a sidereal-time-integrated measurement of z using about 88 million $\Upsilon(4S) \to B\overline{B}$ decays recorded by *BABAR*. With events in which one of two neutral B mesons from an $\Upsilon(4S)$ decay is fully reconstructed as a CP or flavor eigenstate, we measure

$$\begin{aligned}(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\mathrm{Re}\,\mathsf{z} &= 0.014 \pm 0.035(\mathrm{stat.}) \pm 0.034(\mathrm{syst.}),\\ \mathrm{Im}\,\mathsf{z} &= 0.038 \pm 0.029(\mathrm{stat.}) \pm 0.025(\mathrm{syst.}),\end{aligned} \tag{11}$$

where $\lambda_{CP} = (q/p)(\overline{A}_{CP}/A_{CP})$ contains the amplitudes for $\overline{B}^0$ and B^0 decays to the reconstructed CP eigenstate, and $|\lambda_{CP}|$ is of order unity.

Acknowledgments

We are indebted to Alain Milsztajn (deceased) for his help with the periodogram analysis. This contribution was supported by the U.S. Department of Energy, and *BABAR* institutions are supported by the national funding agencies.

[1] D. Colladay and V.A. Kostelecký, Phys. Rev. D **55**, 6760 (1997); Phys. Rev. D **58**, 116002 (1998); V.A. Kostelecký, Phys. Rev. D **69**, 105009 (2004).
[2] V.A. Kostelecký, Phys. Rev. Lett. **80**, 1818 (1998).
[3] B. Aubert *et al.* (*BABAR* Collaboration), hep-ex/0607103.
[4] V.A. Kostelecký, Phys. Rev. D **64**, 076001 (2001).
[5] H. Nguyen (KTeV Collaboration), in V.A. Kostelecký, ed., *CPT and Lorentz Symmetry II*, World Scientific, Singapore, 2002.
[6] J.M. Link *et al.* (FOCUS Collaboration), Phys. Lett. B **556**, 7 (2003).
[7] Y.B. Hsiung (KTeV Collaboration), Nucl. Phys. B (Proc. Suppl.) **86**, 312 (2000).
[8] V.A. Kostelecký and C.D. Lane, Phys. Rev. D **60**, 116010 (1999).
[9] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **70**, 012007 (2004).
[10] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods **A479**, 1 (2002).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **96**, 251802 (2006).
[12] K. Anikeev *et al.* (Heavy Flavor Averaging Group), hep-ex/0505100.
[13] N.R. Lomb, Astrophys. Space Sci., **39**, 447 (1976); J.D. Scargle, Astrophys. J, **263**, 835 (1982).