A Search for CP(T) Violation in B Decays at OPAL

Robin Coxe
Enrico Fermi Institute, University of Chicago

A search for CP(T) violation is performed and the fractional difference between the b and $\bar{\text{b}}$ hadron lifetimes is measured using reconstructed secondary vertices in inclusive B hadron decays selected from 3.1 million $\text{Z}^0 \rightarrow \text{q}\bar{\text{q}}$ events. The data were collected by the OPAL experiment at the LEP collider at CERN at $\sqrt{\text{s}} \approx 91$ GeV from 1991-1995.

I. INTRODUCTION

CP violation in the B-meson system has generated considerable experimental and theoretical interest, as potentially large effects are expected. Searches for CP(T) violation using the small sample of $\text{Z}^0 \rightarrow \text{b}\bar{\text{b}}$ decays at the LEP collider at CERN provide "proofs of principle" for analysis techniques which will be employed by future B-Factory experiments.

Indirect CP violation is possible in the B^0 system provided the weak eigenstates B^0 and $\bar{\text{B}}^0$ differ from the mass eigenstates B_1 and B_2:

$$|\text{B}_1> = \frac{(1+\epsilon_B+\delta_B)|\text{B}^0> + (1-\epsilon_B-\delta_B)|\bar{\text{B}}^0>}{\sqrt{2\left(1+|\epsilon_B+\delta_B|^2\right)}} \tag{1}$$

$$|\text{B}_2> = \frac{(1+\epsilon_B-\delta_B)|\text{B}^0> - (1-\epsilon_B+\delta_B)|\bar{\text{B}}^0>}{\sqrt{2\left(1+|\epsilon_B-\delta_B|^2\right)}}, \tag{2}$$

where ϵ_B and δ_B parametrize CP and CPT violation, respectively [1]. These parameters have been investigated using semileptonic b hadron decays, resulting in limits of order 10^{-2} on both ϵ_B and δ_B [2–5]. In the Standard Model, $\text{Re}(\epsilon_\text{B})$ is expected to be around 10^{-3} [6], but it could be up to an order of magnitude larger in superweak models [7].

A non-zero value of ϵ_B gives rise to a time-dependent rate asymmetry, A(t), in inclusive B^0 *vs.* inclusive $\bar{\text{B}}^0$ decays [6], defined as:

$$\text{A(t)} \equiv \frac{\text{B}^0(\text{t}) - \bar{\text{B}}^0(\text{t})}{\text{B}^0(\text{t}) + \bar{\text{B}}^0(\text{t})}, \tag{3}$$

where $\text{B}^0(\text{t})$ and $\bar{\text{B}}^0(\text{t})$ are the decay rates of B^0 and $\bar{\text{B}}^0$ mesons. For an unbiased selection of B^0 and $\bar{\text{B}}^0$ mesons, the time-dependent inclusive decay rate asymmetry can be rewritten in terms of proper decay time t:

$$A(t) = a_{cp}\left[\frac{\Delta m_d \tau_{B^0}}{2}\sin(\Delta m_d t) - \sin^2\left(\frac{\Delta m_d t}{2}\right)\right], \tag{4}$$

where a_cp is the CP-violating observable, Δm_d is the B^0 oscillation frequency, and τ_{B^0} is the B^0 lifetime. For $|\epsilon_B| << 1$, the parameter a_cp is related to ϵ_B by: $\text{Re}(\epsilon_\text{B}) = \text{a}_\text{cp}/4$.

Furthermore, CPT invariance implies that $\tau_b = \tau_{\bar{b}}$. If CPT violation occurred, the lifetimes of b and $\bar{\text{b}}$ hadrons could be different:

$$\tau_{b/\bar{b}} = \left[1 \pm \frac{1}{2}\left(\frac{\Delta\tau}{\tau}\right)_b\right]\tau_{av}, \tag{5}$$

where τ_av is the average and $(\Delta\tau/\tau)_\text{b}$ is the fractional difference in lifetimes.

II. INCLUSIVE CP(T) TESTS

The measurement of the time-dependent rate asymmetry, A(t), and the extraction of $\mathrm{Re}(\epsilon_B)$ proceeds in several steps. First, selected $Z^0 \to q\bar{q}$ events are divided into 2 hemispheres defined by the plane $\perp$ to thrust axis and containing the e^+e^- interaction point. A sample of about 400,000 $Z^0 \to b\bar{b}$ events is identified using b-tagging techniques described in detail in [8–11]. The b-tags rely on the presence of a displaced secondary vertex or a high momentum lepton. In each event, the hemisphere containing the b-tag is referred to as the "T-tagged" hemisphere. The b-tag has a ϵ_{hemi} of 37 % for $b\bar{b}$ events and a non-b impurity of 13%. Next, the b hadron proper decay time, t, in the opposite "measurement" hemisphere is reconstructed by forming a secondary vertex, measuring the decay distance from the primary vertex, and estimating the b hadron energy. The quantity a_{cp} is then extracted via a binned χ^2-fit to the observed time-dependent asymmetry in bins of reconstructed proper time.

A. Production Flavor Tag

The production flavor estimate, Q_T, in the tagged hemisphere is the output of a neural net with the following inputs:

1. Jet charge of the highest energy jet, Q_{jet}, with (with momentum weight $\kappa = 0.5$). The jet charge is defined as:
$$Q_{jet} = \frac{\Sigma_i (p_i^l)^\kappa q^i}{\Sigma_i (p_i^l)^\kappa q^i}, \tag{6}$$
where p_i^l is the longitudinal momentum component with respect to the jet axis and q_i is the charge of track i.
2. Vertex charge, $Q_{vtx} = \Sigma_i w_i q_i$, where w_i is the weight for track i to have come from a secondary instead of a primary vertex. Weights are derived from an artificial neural network with three inputs: the momentum of track i, the transverse momentum of track i with respect to the jet axis, and the impact parameter.
3. Uncertainty on the vertex charge, $\sigma_{Q_{vtx}} = \Sigma_i w_i (1 - w_i) q_i^2$.
4. The product of lepton charge and output of neural network used to select $b \to l$ decays, a lepton tag.

The jet charge and vertex charge are not charge symmetric due to detector effects resulting in the difference in the rate and reconstruction of positively and negatively charged tracks. Offsets are evaluated using inclusive samples of T-tagged events and are subtracted prior to constructing Q_T. The lepton tag is diluted by b mixing, cascade b decays, c decays, and fake leptons. Separate networks with fewer inputs are trained for events with a vertex or a lepton only.

The variable Q_T is defined as:
$$Q_T = \frac{N_b(x) - N_{\bar{b}}(x)}{N_b(x) + N_{\bar{b}}(x)} \tag{7}$$
$$|Q_T| = 1 - 2\eta, \tag{8}$$

where $N_b(x)$ and $N_{\bar{b}}(x)$ are the numbers of MC b and $\bar{b}$ hadron hemispheres with a given value of artificial neural network output x and η is the mistag probability. If $Q_T > 0$, then the tagged hemisphere is more likely to contain a b hadron than a $\bar{b}$ hadron, and vice versa. If $Q_T = 0$, both hypotheses are equally likely.

The Q_T flavor tag has some sensitivity to the *decay* flavor of the tagged hemisphere, which is not desirable in an inclusive measurement. Therefore, another tag Q_M is applied in the opposite, or measurement, hemisphere. The Q_T output in the T-tagged hemisphere, as well as the jet charge in the measurement hemisphere, Q_M (with momentum weight $\kappa = 0$), are combined to construct the composite variable:

$$Q_2 = 2\left[\frac{(1-Q_T)(1+Q_M)}{(1-Q_T)(1+Q_M)+(1+Q_T)(1-Q_M)}\right] - 1. \tag{9}$$

Again, if $Q_2 > 0$ ($Q_2 < 0$), the so-called "M-tagged" hemisphere contains a b-hadron tag ($\bar{b}$-hadron) tag. The Q_2 variable is designed to be sensitive to the production, but not the decay flavor of the b-hadron, thus avoiding biases to the reconstructed proper time measurement. After flavor tagging, 394119 events remain in the data sample.

B. Proper Decay Time Reconstruction

The CP-violating parameter a_{cp} can be extracted from the rate asymmetry distribution, A(t), as defined in Equation 4. This is accomplished by calculating the number of b-hadron M-tags minus the number of $\bar{b}$-hadron M-tags in bins of reconstructed proper time t and performing a binned χ^2 fit to measure a_{cp}. The b-hadron proper time is defined as:

$$t = \frac{m_b L}{\sqrt{E_b^2 - m_b^2}}, \tag{10}$$

where L is the hadron decay length, E_b is the b-hadron energy, and m_b is the mass of the b-hadron, taken be that of the B^+ and B^0 (5.279 GeV) [12].

The hadron decay length, L, is reconstructed in the measurement hemisphere by first forming a "seed" secondary vertex using the two tracks with the largest impact parameter, d_0, relative to the primary vertex in the highest energy jet. All tracks with $p > 0.5$ GeV, $|d_0| < 1$ cm, and $\sigma_{d_0} < 0.1$ cm, which are consistent with the "seed" vertex are then added to it via an interative procedure. The secondary vertex must contain at least 3 tracks and have an invariant mass exceeding 0.8 GeV, assuming all constituent tracks are pions. To further eliminate badly reconstructed or fake secondary vertices, the secondary vertex must be kinematically consistent with a long-lived particle originating from the primary vertex. Secondary vertices meeting the above criteria are identified in approximately 70% of M-tagged hemispheres for both signal and background. The decay length L between the primary and secondary vertices is then calculated using the jet axis as a constraint.

The b-hadron energy is computed by first estimating the energy of the b-jet by treating the event as a 2-body decay of a Z^0 into a b-jet of mass m_b and another object. The charged and neutral fragmentation energy, E_{bfrag}, was estimated using the procedure described in [13], involving the charged track weights w_i, and the unassociated electromagnetic calorimeter clusters weighted according to their angle with respect to the jet axis. The b-hadron energy is then, $E_b = E_{bjet} - E_{bfrag}$.

The reconstructed proper time distribution described by Equation 10 is convolved with 2 Gaussians to account for detector resolution effects. The RMS widths of the resolution functions are 0.33 and 1.3 ps and are determined from Monte Carlo studies. About 65% of events lie within the narrower Gaussian. These resolution functions represent an average over all true decay proper times t. The non-Gaussian effects apparent in small slices of t due to contamination from primary vertex tracks are not critical in this analysis, as the result is not particularly dependent on accurate decay time resolution.

III. FIT TO RE(ϵ_B)

For each of 34 time bins i (in the range -2 to 15 ps), the asymmetry is calculated in 10 bins j of $|Q_2|$:

$$A_{ij}^{obs} = \frac{N_{ij}^b - N_{ij}^{\bar{b}}}{< |Q_2| >_{ij} (N_{ij}^b + N_{ij}^{\bar{b}})}, \tag{11}$$

and the error $\sigma_{A_{ij}^{obs}}$ is given by:

$$\sigma_{A_{ij}^{obs}} = \frac{1-(<|Q_2|>_{ij}\ A_{ij}^{obs})^2}{2<|Q_2|>_{ij}} \sqrt{\frac{N_{ij}^{b}+N_{ij}^{\bar{b}}}{N_{ij}^{b}N_{ij}^{\bar{b}}}},$$

where N_{ij}^{b} ($N_{ij}^{\bar{b}}$) is the number of events with $Q_2 > 0$ ($Q_2 < 0$). The factor $1/<|Q_2|>_{ij}$ corrects for the tagging dilution (mis-tagging), which reduces the observed asymmetry for imperfectly tagged events.

The 10 estimates of A_{ij}^{obs} in each bin i are then averaged, weighting by $(\sigma_{A_{ij}^{obs}})^{-2}$ to get A_i^{obs}. A binned χ^2-fit to the reconstructed proper time which accounts for non-B^0 background, the B^0 lifetime, and the Gaussian time resolution functions yields:

$$a_{cp} = 0.005 \pm 0.055 \pm 0.013 \tag{12}$$
$$Re(\epsilon_B) = 0.001 \pm 0.014 \pm 0.003. \tag{13}$$

The asymmetry, A(t), as a function for reconstructed proper time t is shown in Figure 1. The dots denote OPAL data, the solid line the fit result, and the dashed line the expected asymmetry for $a_{cp} = 0.15$.

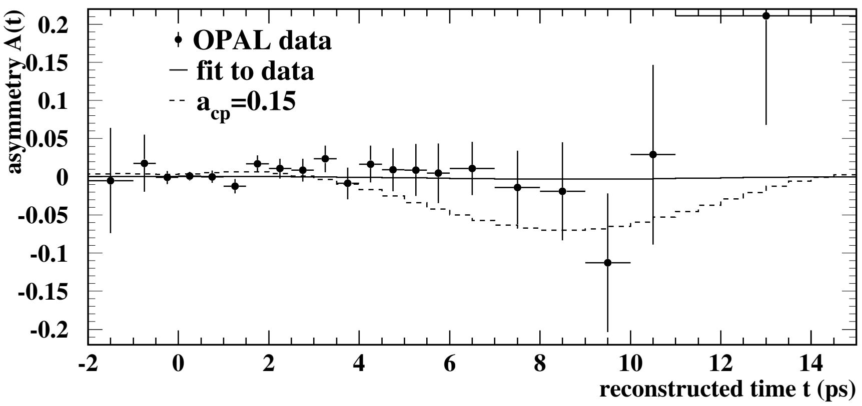

FIG. 1. Asymmetry of tagged b and $\bar{b}$- hadrons as a function of reconstructed time t in data (points), and fit (solid line). The expected asymmetry for $a_{cp} = 0.15$ is shown by the dotted line.

The systematic uncertainties are summarized in Table I. Detailed descriptions of the various contributions can be found in Reference [14]. If the reconstruction efficiency for B^0 decays to different numbers of charm hadrons is not the same, the expected asymmetry could take the form:

$$A(t) = c_{cp} \sin(\Delta m_d t) - a_{cp} \sin^2(\Delta m_d t/2). \tag{14}$$

Repeating the fit, letting both a_{cp} and c_{cp} vary gives:

$$a_{cp} = 0.002 \pm 0.055 \tag{15}$$
$$c_{cp} = 0.026 \pm 0.027. \tag{16}$$

Differences in efficiency are not significant, as a_{cp} does not change much. The systematic uncertainties on the measurement of c_{cp} are listed in the second column of Table I.

IV. FIT TO $(\Delta\tau/\tau)_B$

The fractional difference between the b and $\bar{b}$- hadron lifetimes is measured by dividing the data into 20 bins of Q_2 (related to b/$\bar{b}$-hadron purity) and performing a simultaneous fit of the reconstructed proper time distrbutions to the

TABLE I. Systematic uncertainties on the measurements of a_{cp} and c_{cp}.

Source	Δa_{cp}	Δc_{cp}
B^0 lifetime	0.002	0.000
Δm_d value	0.001	0.001
B^0 fraction	0.002	0.002
Flavor tagging offsets	0.003	0.013
Flavor tagging mis-tag	0.009	0.005
b fragmentation	0.008	0.006
Time resolution	0.002	0.000
Total	0.013	0.015

expected proper time distribution. The fit yields values for both τ_{avg} and $(\Delta\tau/\tau)_b$. However, the result for τ_{avg} has a large systematic uncertainty due to the time resolution function and should not be interpreted as a measurement of the average b-hadron lifetime. The expected distribution accounts for time resolution effects, non-b$\bar{b}$ background, the lifetimes of b and $\bar{b}$-hadrons, and a background component with a lifetime τ_{bg}. The fit result is:

$$(\Delta\tau/\tau)_b = -0.001 \pm 0.012 \pm 0.008. \tag{17}$$

The uncertainty in the flavor mistag rate dominates the systematic uncertainty on $(\Delta\tau/\tau)_b$. Reconstructed proper time distributions in 4 ranges of Q_2 are shown in Figure 2.

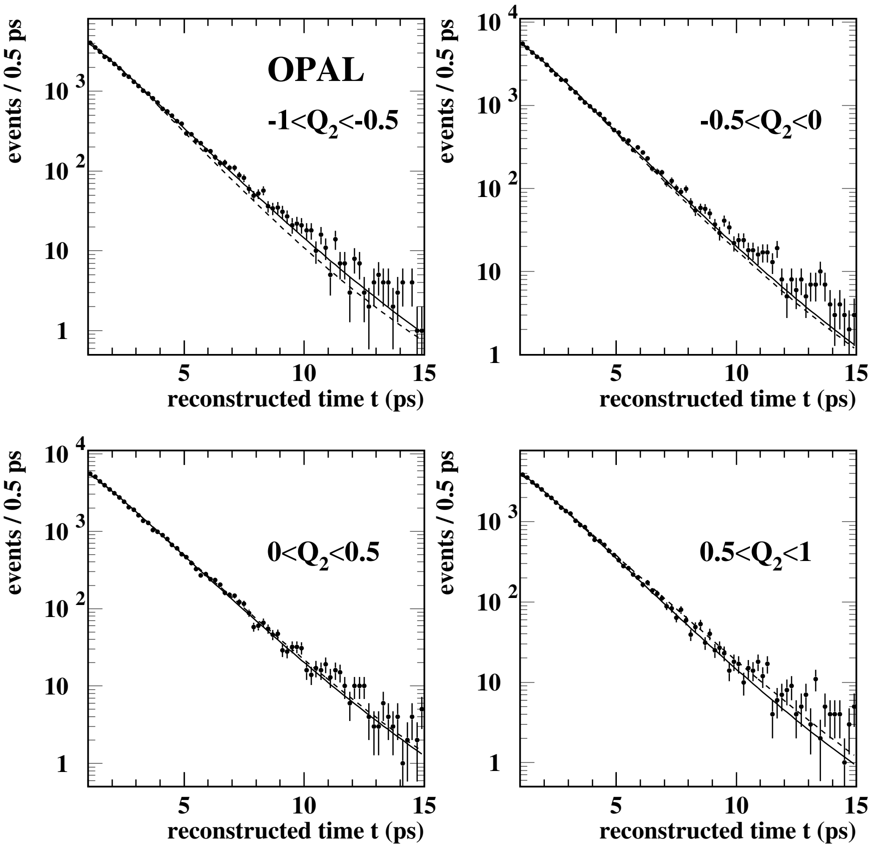

FIG. 2. Reconstructed proper time distributions in four ranges of Q_2. The data are shown by the points with error bars and the fit prediction by the solid lines. The expected distributions for $(\Delta\tau/\tau)_b = 0.2$ are shown by the dotted lines.

V. CONCLUSION

An inclusive sample of b-hadron decays is used to search for CP and CPT violation effects. No such effects are seen. From the time dependent asymmetry of inclusive B^0 decays, the CP violation parameter is measured to be:

$$Re(\epsilon_B) = 0.001 \pm 0.014 \pm 0.003. \tag{18}$$

This result agrees with the OPAL measurement using semileptonic b decays: $\mathrm{Re}(\epsilon_\mathrm{B}) = 0.002 \pm 0.007 \pm 0.003$ [4], and is also in agreement with other less precise results from CLEO and CDF [3]. The fractional difference in the lifetimes of b and $\bar{\mathrm{b}}$-hadrons is also measured to be:

$$(\Delta\tau/\tau)_b = -0.001 \pm 0.012 \pm 0.008. \tag{19}$$

This is the first analysis accepted for publication which tests the equality of the b and $\bar{\mathrm{b}}$-hadron lifetimes. These results are summarized in Figures 3 and 4.

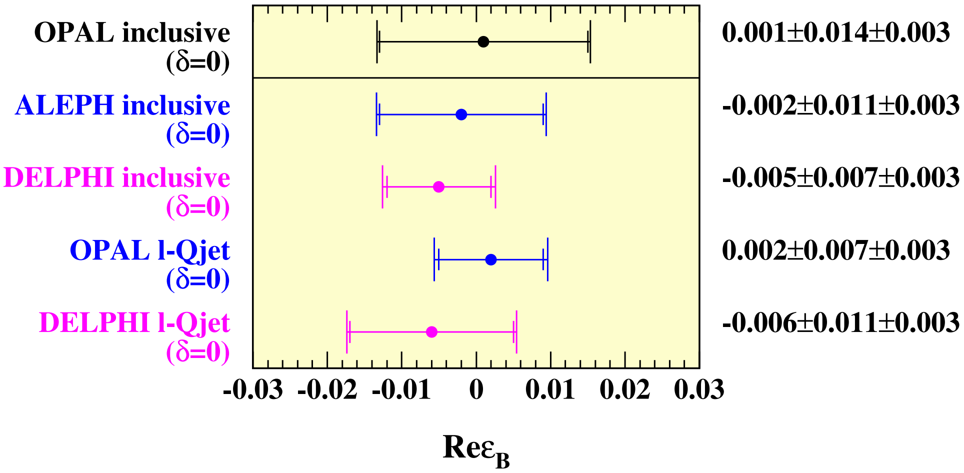

FIG. 3.

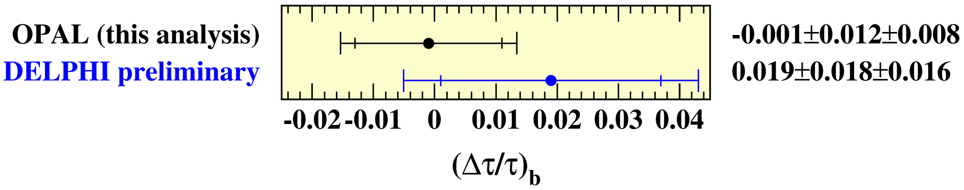

FIG. 4.

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