Search for T and CP Violation in B^0-$\overline{B}^0$ Mixing with Inclusive Dilepton Events

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We report the results of a search for T and CP violation in B^0-$\overline{B}^0$ mixing using an inclusive dilepton sample collected by the *BABAR* experiment at the PEP-II B Factory. The asymmetry between $\ell^+\ell^+$ and $\ell^-\ell^-$ events allows us to compare the probabilities for $\overline{B}^0 \rightarrow B^0$ and $B^0 \rightarrow \overline{B}^0$ oscillations and thus probe T and CP invariance. Using a sample of 23×10^6 $B\overline{B}$ pairs, we measure a same-sign dilepton asymmetry of $A_{T/CP} = [0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst})]\%$. For the modulus of the ratio of complex mixing parameters p and q, we obtain $|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst})$.

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Since the first observation of CP violation in 1964 [1], the neutral kaon system has provided many other results probing the CPT and T discrete symmetries [2]. Beyond the investigation of CP violation through the measurements of the unitarity triangle angles α, β, and γ, the *BABAR* experiment can investigate T and CP violation purely in B^0-$\overline{B}^0$ mixing.

The physical states (solutions of the complex effective Hamiltonian for the B^0-$\overline{B}^0$ system) can be written as

$$|B^0_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle,$$

where p and q are complex mixing parameters with the normalization $|p|^2 + |q|^2 = 1$.

The CPT invariant asymmetry, $A_{T/CP}$, between the two oscillation probabilities $P(\overline{B}^0 \to B^0)$ and $P(B^0 \to \overline{B}^0)$ probes both T and CP symmetries and can be expressed in terms of p and q:

$$A_{T/CP} = \frac{P(\overline{B}^0 \to B^0) - P(B^0 \to \overline{B}^0)}{P(\overline{B}^0 \to B^0) + P(B^0 \to \overline{B}^0)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}. \quad (1)$$

Standard model calculations [3] predict the size of this asymmetry to be at or below 10^{-3}. Therefore, a large measured value could be an indication of new physics.

Inclusive dilepton events, representing 4% of all $\Upsilon(4S) \to B\overline{B}$ decays, provide a very large sample with which to study T and CP violation in mixing. The flavor of each B meson is tagged by the charge of the lepton. Assuming $\Delta B = \Delta Q$ and CP invariance in the direct $b \to \ell$ semileptonic decay process, the asymmetry between same-sign lepton pairs, $\ell^+\ell^+$ and $\ell^-\ell^-$, allows a comparison of the two oscillation probabilities $P(\overline{B}^0 \to B^0)$ and $P(B^0 \to \overline{B}^0)$. The asymmetry $A_{T/CP}$ for direct same-sign dileptons is time independent. However, in this analysis, the time difference Δt between the two B meson decays is used to discriminate the direct leptons from the cascade leptons produced in $b \to c \to \ell$ transitions.

The measurement of $A_{T/CP}$ reported here is performed with events collected by the *BABAR* detector [4] from e^+e^- collisions at the PEP-II asymmetric-energy B Factory between October 1999 and October 2000. The integrated luminosity of this sample is 20.7 fb^{-1} recorded at the $\Upsilon(4S)$ resonance ("on-resonance") and 2.6 fb^{-1} recorded about 40 MeV below the $\Upsilon(4S)$ resonance ("off-resonance"). $B\overline{B}$ pairs from the $\Upsilon(4S)$ decay move along the high-energy beam direction (z) with a nominal Lorentz boost $\langle\beta\gamma\rangle = 0.55$.

Non-$B\overline{B}$ events are suppressed by requiring the ratio of second to zeroth order Fox-Wolfram moments [5] to be less than 0.4. In addition, residual contamination from radiative *Bhabha* and two-photon events is reduced by requiring the squared invariant mass of the event to be greater than 20 GeV^2/c^4, the event aplanarity to be greater than 0.01, and the number of charged tracks to be greater than four.

Lepton candidates must have at least 12 hits in the drift chamber (DCH), at least one z-coordinate hit in the silicon vertex tracker (SVT), and a momentum in the $\Upsilon(4S)$ center-of-mass system (CMS) between 0.7 and 2.5 GeV/c. Electrons are selected by requirements on the ratio of the energy deposited in the electromagnetic calorimeter (EMC) and the momentum measured in the DCH, on the lateral shape of the energy deposition in the calorimeter, and on the specific ionization density measured in the DCH. Muons are identified through the energy released in the calorimeter, as well as the strip multiplicity, track continuity, and penetration depth in the instrumented flux return (IFR). Lepton candidates are rejected if they are consistent with a kaon or proton hypothesis according to the Cherenkov angle measured in the detector of internally reflected Cherenkov light (DIRC) or to the ionization density measured in the DCH. The electron and muon selection efficiencies are about 92% and 75%, with pion misidentification probabilities around 0.2% and 3%, respectively.

Electrons from photon conversions are identified and rejected with a negligible loss of efficiency for signal events. Leptons from J/ψ and $\psi(2S)$ decays are identified by pairing them with other oppositely charged candidates of the same-lepton species, selected with looser criteria. We reject the whole event if any combination has an invariant mass within $3.037 < M(\ell^+\ell^-) < 3.137$ GeV/c^2 or $3.646 < M(\ell^+\ell^-) < 3.726$ GeV/c^2.

To minimize wrong flavor tags due to leptons from cascade charm decays, we use a neural network (NN) algorithm that combines five discriminating variables. These are calculated in the CMS (see Fig. 1) and are the momenta of the two leptons with highest momentum, p_1^* and p_2^*, the total visible energy E_{tot}, the missing momentum p_{miss} of the event, and the opening angle between the leptons,

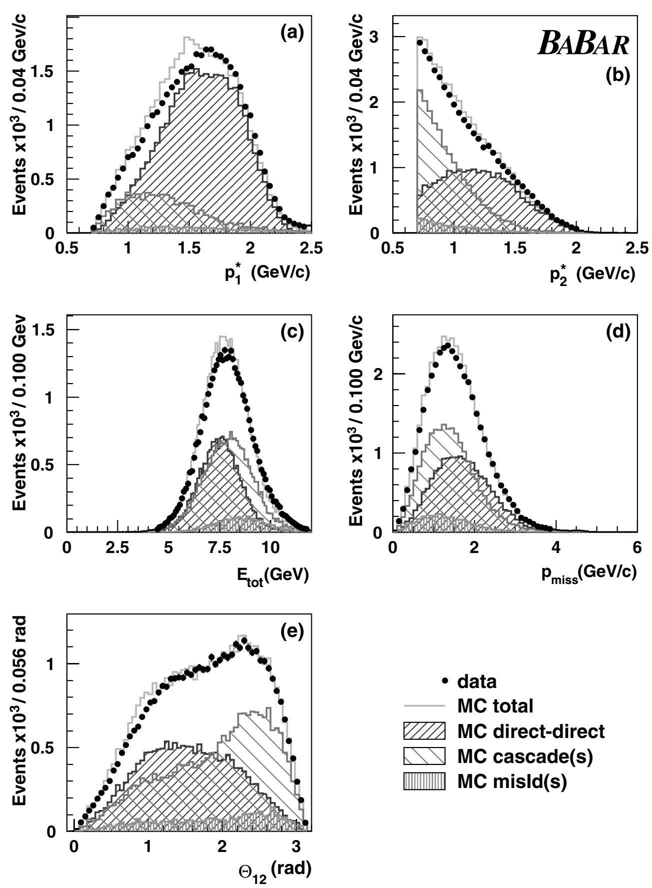

FIG. 1. Distributions of the discriminating variables (a) p_1^*, (b) p_2^*, (c) E_{tot}, (d) p_{miss}, and (e) θ_{12}, for data (dots) and Monte Carlo events (histograms). The contributions from direct-direct pairs, direct-cascade, or cascade-cascade pairs, and pairs with one or more fake leptons are shown for the Monte Carlo samples.

θ_{12}. The first two variables, p_1^* and p_2^*, are very powerful in discriminating between direct and cascade leptons. The last variable, θ_{12}, efficiently removes direct-cascade lepton pairs coming from the same B, and further rejects photon conversions. Some additional discriminating power is also provided by the other two variables. The two NN outputs are each required to be greater than 0.8. In order to be insensitive to the small discrepancies between data and Monte Carlo, the fraction of cascade leptons is determined from a fit to the same-sign and opposite-sign dilepton data.

In the inclusive approach used here, the z coordinate of the B decay point is the z position of the point of closest approach between the lepton candidate and an estimate of the $\Upsilon(4S)$ decay point in the transverse plane. The $\Upsilon(4S)$ decay point is obtained by fitting the two lepton tracks to a common vertex in the transverse plane, which is constrained to be consistent with the beam-spot position. The proper time difference Δt between the two B meson decays is determined from the absolute value, Δz, of the difference in z between the two B decays by $\Delta t = \Delta z / \langle \beta\gamma \rangle c$. The same-sign background events (cascade leptons from unmixed $B^0\overline{B}^0$ events and B^+B^- events, and non-$B\overline{B}$ events) are most prominent at low Δz (see Fig. 2). Therefore, a requirement of $\Delta z > 200\ \mu$m allows us to eliminate about 50% of background without dramatically decreasing the signal efficiency.

Application of the selection criteria described above results in a sample of 20 381 same-sign dilepton events, consisting of 5252 electron pairs, 5152 muon pairs, and 9977 electron-muon pairs. The fraction of non-$B\overline{B}$ events, measured with the off-resonance data, is 4.3% with a charge asymmetry of $(-5 \pm 10)\%$. The main $B\overline{B}$ backgrounds, determined with Monte Carlo simulation, include 24% of one direct lepton paired with a cascade lepton from the other B, 10% of fake leptons from the other B, 2% of fake leptons from the same B, and 2% of leptons from J/ψ resonance decays.

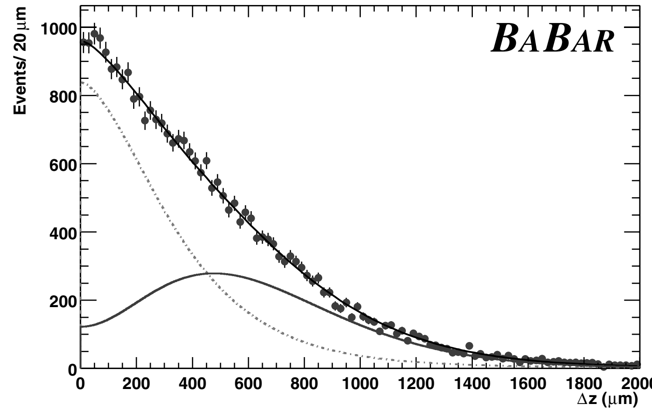

FIG. 2. Distribution of the same-sign dileptons as a function of Δz. The curve superimposed on the dots is determined from a fit to the same-sign and opposite-sign dileptons. The solid and dotted lines represent, respectively, the signal component (B^0B^0 or $\overline{B}^0\overline{B}^0$ pairs) and the background component (cascade leptons, leptons from J/ψ, resonance decays, non-$B\overline{B}$ events, and fake leptons).

Since the asymmetry $A_{T/CP}$ is expected to be small, we have carefully determined the possible charge asymmetries induced by the detection and reconstruction of electrons and muons. The three sources of charge asymmetry in the selection of lepton candidates come from differences, for positive and negative particles, in tracking efficiency $\varepsilon^{\pm}_{\rm track}$, in particle identification efficiency $\varepsilon^{\pm}_{\rm pid}$, and in misidentification probability $\eta^{\pm}_{\rm pid}$. Independent samples are used to estimate these efficiencies and probabilities separately for electrons and muons as a function of several charged track parameters x_i: total or transverse momentum, and polar and azimuthal angles in the laboratory frame. The numbers of "detected" positive and negative leptons ($N^{\pm}_{\rm det}$) are related to the numbers of true leptons ($N^{\pm}_{\rm true}$) by the equation

$$N^{\pm}_{\rm det}(x_i, p^*) = N^{\pm}_{\rm true}(x_i, p^*)\varepsilon^{\pm}_{\rm track}(x_i)[\varepsilon^{\pm}_{\rm pid}(x_i) + r(\pi, p^*)\eta^{\pm}_{\rm pid}(\pi, x_i) + r(K, p^*)\eta^{\pm}_{\rm pid}(K, x_i) + r(p, p^*)\eta^{\pm}_{\rm pid}(p, x_i)], \qquad (2)$$

where $r(\pi, p^*)$, $r(K, p^*)$, and $r(p, p^*)$ are the relative abundances of hadrons (π, K, and p) with respect to the lepton abundance for a given p^* (the momentum of the track in the CMS). These quantities are obtained from $B\overline{B}$ Monte Carlo events, after applying the event selection criteria with perfect particle identification. To correct for charge asymmetries in lepton detection, we apply a weight proportional to the ratio $N^{\pm}_{\rm true}(x_i, p^*)/N^{\pm}_{\rm det}(x_i, p^*)$ for each lepton in the sample.

Using tracks selected from multihadron events, the tracking efficiencies $\varepsilon^{\pm}_{\rm track}(x_i)$ for positive and negative particles are determined by computing the ratio of the number of SVT tracks with and without the dilepton selection requirement of at least 12 DCH hits. These tracking efficiencies are tabulated as a function of transverse momentum, and polar and azimuthal angles. The charge asymmetry in tracking efficiency is less than 0.1% on average in the relevant momentum range.

The identification efficiencies $\varepsilon^{\pm}_{\rm pid}(x_i)$ are measured as a function of total momentum and polar and azimuthal angles, with two control samples consisting of $ee \to eeee$ (with $\gamma\gamma \to ee$) and radiative *Bhabha* events for electrons, and with a $ee \to ee\mu\mu$ (with $\gamma\gamma \to \mu\mu$) control sample for muons. The misidentification probabilities $\eta^{\pm}_{\rm pid}(\text{hadron}, x_i)$ are determined with control samples of kaons produced in $D^{*+} \to \pi^+ D^0 \to \pi^+ K^- \pi^+$ decays (and charge conjugate), pions produced in $K_S \to \pi^+\pi^-$ decays as well as in one-prong and three-prong τ decays, and protons produced in Λ decays.

For the electrons, the charge asymmetry in the particle identification efficiency reaches (0.5–1.0)% in some regions of the lepton phase space. The impact of the charge asymmetry in misidentification is negligible because the absolute misidentification probability for pions is extremely small (~0.2%). However, the Λ control sample indicates a very large misidentification probability for antiprotons with momentum ~1 GeV/c. Such an effect is due to the annihilation of antiprotons with nucleons in the calorimeter, which produces a signature similar to that of an electron. The impact of this effect is balanced by the low relative abundance of antiprotons in B decays. Overall, antiprotons induce a charge asymmetry of order 0.1% and a correction is applied for this effect.

For the muons, the $ee\mu\mu$ control sample shows that the charge asymmetry in the efficiency reaches 0.5%. The pion misidentification probability is much larger (~3%) than in the case of electrons but there is no indication of any charge asymmetry induced. On the other hand, the kaon misidentification distribution shows a charge asymmetry at the level of (10–20)% due to the difference between the cross sections for K^+ and K^- meson interactions with matter for momenta around 1 GeV/c.

Equation (1) is applicable for pure signal (direct leptons from B^0B^0 and $\overline{B}^0\overline{B}^0$ events). However, the dilepton sample is contaminated by cascade leptons from B^+B^- and unmixed $B^0\overline{B}^0$ events, non-$B\overline{B}$ events, and J/ψ decays (see Fig. 2). Assuming no charge asymmetry in the background and CP invariance in direct semileptonic B decays, we can write the measured asymmetry $A_{T/CP}^{\rm meas}$ in terms of the weighted number of events N as

$$A_{T/CP}^{\rm meas}(\Delta t) = \frac{N(\ell^+\ell^+, \Delta t) - N(\ell^-\ell^-, \Delta t)}{N(\ell^+\ell^+, \Delta t) + N(\ell^-\ell^-, \Delta t)} = A_{T/CP}\frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}, \quad (3)$$

where $S(\Delta t)$ and $B(\Delta t)$ are the numbers of signal and background events, respectively. Therefore, extraction of a value for $A_{T/CP}$ requires a determination of the dilution factor $S(\Delta t)/[S(\Delta t) + B(\Delta t)]$. The asymmetry between same-sign dileptons is corrected for the background dilution using the time-dependent probability density functions shown in Fig. 2. These probability density functions are obtained with a simultaneous fit to the same-sign and opposite-sign dilepton samples, with the values of Δm_d, B^0, and B^+ lifetimes fixed to the world average values [6]. This fit is similar to that used in the measurement of Δm_d with dilepton events [7]: it determines the corrections to the resolution function extracted from Monte Carlo simulation, the fraction of cascade leptons, the average lifetime of the charm component for cascade leptons, and the fraction of charged B events. A possible dilution of $A_{T/CP}$ due to double mistag (both leptons from cascade decays) is neglected because the probability of double mistag is at the level of only 1%. In addition, the fraction of non-$B\overline{B}$ events is measured from off-resonance data. From a χ^2 fit of the measured asymmetry as a function of Δt for the same-sign dileptons with $\Delta z > 200\ \mu$m (see Fig. 3), we extract $A_{T/CP} = (0.5 \pm 1.2)\%$.

Systematic uncertainties related to possible charge asymmetry both for tracking and lepton identification are determined with single direct leptons from semileptonic B decays. This sample has the same topology and kinematics as leptons in dilepton events. The single-lepton charge asymmetry, in addition to being sensitive to the charge asymmetry from detection bias, may also be affected by the real physical asymmetry $A_{T/CP}$ in the dilepton events. But, in practice, any contribution introduced by a nonzero $A_{T/CP}$ is suppressed by more than 1 order of magnitude and is therefore neglected. We select roughly 1.5×10^6 electrons and 1.5×10^6 muons. After subtraction of scaled off-resonance data and applying a correction weight derived from Eq. (2), we measure the charge asymmetries to be $(-0.30 \pm 0.14)\%$ for the electrons and $(-0.35 \pm 0.17)\%$ for the muons. We assign these residual asymmetries $\pm 0.30\%$ and $\pm 0.35\%$ as systematic errors due to charge asymmetry in detection efficiencies. With the dilution factor correction, the total systematic errors related to the charge asymmetry in detection are $\pm 0.5\%$ and $\pm 0.6\%$ for electrons and muons, respectively.

The assumption of no charge asymmetry in the background is confirmed by the off-resonance data where the charge asymmetry $(-5 \pm 10)\%$ is consistent with zero and leads to a $\pm 0.7\%$ uncertainty on the $A_{T/CP}$ measurement. In addition, the charge asymmetry of the events with $\Delta z < 100\ \mu$m, which contain 85% background (cascade leptons from $B^\pm$ and unmixed B^0), is $(1.2 \pm 1.4)\%$, also consistent with zero. From this asymmetry, we can constrain to $\pm 0.9\%$ the uncertainty on $A_{T/CP}$ from a possible

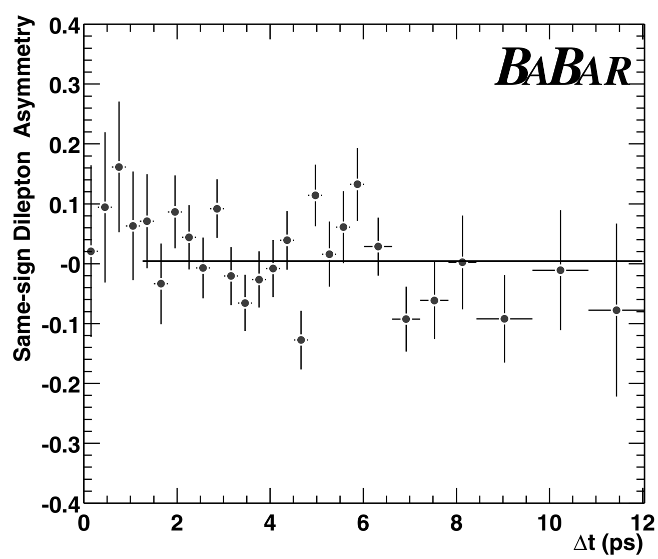

FIG. 3. Corrected same-sign dilepton asymmetry as a function of Δt. The line shows the result of the fit for the dileptons with $\Delta z > 200\ \mu$m.

TABLE I. Summary of systematic uncertainties on $A_{T/CP}$.

Type of systematic error	$\sigma(A_{T/CP})$ (%)
Electron charge asymmetry in the detection	0.5
Muon charge asymmetry in the detection	0.6
Non-$B\overline{B}$ background charge asymmetry	0.7
$B\overline{B}$ background charge asymmetry	0.9
Correction of the background dilution	0.01
Total	1.4

charge asymmetry in the decays producing the cascade leptons. If we assume CP invariance in the decays producing the cascade, this uncertainty vanishes.

The background dilution correction is measured with the data from the full dilepton sample. The uncertainty on the ratio B/S leads to a $\pm 3\%$ multiplicative error on $A_{T/CP}$, which is negligible.

In conclusion, we measure $A_{T/CP} = [0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst})]\%$ where the total systematic uncertainty is the quadratic sum of the systematic uncertainties listed in Table I. From Eq. (1), the result for $A_{T/CP}$ can be used to extract the modulus of the ratio of complex mixing parameters p and q:

$$|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst}).$$

This measurement can also be expressed in terms of the CP violating parameter $\varepsilon_B = (p - q)/(p + q)$. We obtain $\text{Re}(\varepsilon_B)/(1 + |\varepsilon_B|^2) = [1.2 \pm 2.9(\text{stat}) \pm 3.6(\text{syst})] \times 10^{-3}$, which is the most stringent test of T and CP violation in B^0-$\overline{B}^0$ mixing to date and is consistent with previous measurements [8].

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