Bounds on the CP Asymmetry in Like-Sign Dileptons from $B^0\bar{B}^0$ Meson Decays

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We have measured the charge asymmetry in like-sign dilepton yields from $B^0\bar{B}^0$ meson decays using the CLEO detector at the Cornell Electron Storage Ring. We find $a^0_{\ell\ell} \equiv [N(\ell^+\ell^+) - N(\ell^-\ell^-)]/[N(\ell^+\ell^+) + N(\ell^-\ell^-)] = +0.013 \pm 0.050 \pm 0.005$. We combine this result with a previous, independent measurement and obtain $\mathrm{Re}(\epsilon_B)/(1 + |\epsilon_B|^2) = +0.0035 \pm 0.0103 \pm 0.0015$ (uncertainties are statistical and systematic, respectively) for the CP impurity parameter, ϵ_B.

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The neutral B mesons mix, just as the neutral kaons do. $K^0 - \bar{K}^0$ mixing violates CP, with different rates for $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$. The standard model predicts that the mixing rates $B^0 \to \bar{B}^0$ and $\bar{B}^0 \to B^0$ are very nearly equal. Thus, a CP asymmetry in $B^0 - \bar{B}^0$ mixing would be evidence for nonstandard-model physics.

The mass eigenstates of the neutral B system may be written as $B_{1,2} = [(1 + \epsilon_B)B^0 \pm (1 - \epsilon_B)\bar{B}^0]/\sqrt{2(1 + |\epsilon_B|^2)}$, where ϵ_B is the "CP impurity parameter," analogous to the CP violation parameter ϵ of K^0 mixing. If the real part of ϵ_B is nonzero, then a CP asymmetry exists. In an $\Upsilon(4S) \to B^0\bar{B}^0$ event where both B mesons undergo semileptonic decay, the presence of like-sign dileptons indicates mixing. A charge asymmetry of such events, $a_{\ell\ell} \equiv [N(\ell^+\ell^+) - N(\ell^-\ell^-)]/[N(\ell^+\ell^+) + N(\ell^-\ell^-)]$, indicates a CP violation, related to $\mathrm{Re}(\epsilon_B)$ by $a_{\ell\ell} = 4\,\mathrm{Re}(\epsilon_B)/(1 + |\epsilon_B|^2)$. For a review of the formalism, see Ref. [1].

The lepton charge asymmetry in $B\bar{B}$ decays with a single charged lepton, a_ℓ, also measures the CP violation parameter but with reduced sensitivity, because B^+B^- and unmixed $B^0\bar{B}^0$ events contribute. In particular [1],

$$a_\ell = \chi_d[f_{00}\tau_0^2/(f_{00}\tau_0^2 + f_{+-}\tau_\pm^2)]a_{\ell\ell}. \qquad (1)$$

Here f_{00} (f_{+-}) is the fraction of $\Upsilon(4S)$ decays leading to $B^0\bar{B}^0$ (B^+B^-), τ_0 ($\tau_\pm$) is the lifetime of the neutral (charged) B meson, and χ_d is the neutral B mixing parameter, the ratio of mixed events to mixed plus nonmixed neutral events.

The standard model prediction [2] for $\mathrm{Re}(\epsilon_B)$ is $\sim 10^{-3}$, while superweak models have predictions [3] up to an order of magnitude larger. Previous searches by us [4,5] and by others [6–9] have found no evidence for CP violation within a statistical accuracy ranging from ± 0.07 to ± 0.01 in $\mathrm{Re}(\epsilon_B)$.

In this Letter we report a measurement of dilepton asymmetry, using a new technique and 10 times more data than our previous dilepton measurement [4]. With this increased statistical accuracy we reduce systematic errors by combining single lepton asymmetries with dilepton asymmetries. This technique renders our systematic errors negligible and is appropriate for B-factory-sized data samples of hundreds of inverse femtobarns.

The data used in this analysis were taken with the CLEO detector at the Cornell Electron Storage Ring (CESR), a symmetric e^+e^- collider. Our sample consists of 9.1 fb^{-1} on the Υ(4S) resonance, and 4.4 fb^{-1} at a center-of-mass energy $\sim$60 MeV below the resonance. The on-resonance sample contains 10×10^6 $B\bar{B}$ events and 30×10^6 continuum events, while the off-resonance sample contains 15×10^6 continuum events.

The CLEO detector [10] measures charged particle momenta over 95% of 4π steradians with a system of cylindrical drift chambers immersed in a 1.5 T solenoidal magnetic field. For 2/3 of the data used here, the innermost tracking chamber was a three-layer silicon vertex detector [11]. The CLEO barrel and end cap CsI electromagnetic calorimeters cover 98% of 4π. Charged particle species are identified by specific ionization measurements (dE/dX) in the outermost drift chamber and by time-of-flight counters placed just beyond the tracking volume.

Muons are identified by their ability to penetrate the iron return yoke of the magnet (at least five interaction lengths of material in this analysis). Electrons are identified by shower energy to momentum ratio (E/P), track-cluster matching, dE/dX, and shower shape. For angles relative to the beam line of less than 45°, electrons pass through the thick end plates of the drift chamber, and the quality of electron identification degrades. We make a distinction between "central electrons," with $|\cos\theta| \le 0.7$, and "noncentral electrons," with $|\cos\theta| > 0.7$.

In this analysis, we wish to count single leptons and lepton pairs, with all leptons coming from the primary semileptonic decay of B mesons. There are backgrounds from secondary decays $b \to c \to s\ell\nu$, from $B \to \psi \to \ell^+\ell^-$, from pair-converted photons, from hadrons misidentified as leptons, and from continuum events. To reduce these backgrounds, we do the following: require that the leptons have high momentum, 1.6–2.4 GeV/c; veto leptons that form a J/ψ or ψ' candidate with any other loosely identified, same-flavor, opposite-charge lepton in the event; and veto electrons that appear to originate from photon conversions. The momentum requirement eliminates our sensitivity to leptons from taus involved in semileptonic B decays. In counting lepton pairs, we allow at most one lepton to be an electron from the noncentral region. To suppress continuum events in lepton pairs, we require that the leptons be noncollinear, with the angle $\theta_{\ell\ell}$ between them satisfying $-0.8 < \cos\theta_{\ell\ell} < +0.9$ (the 0.9 limit eliminates a rare tracking error where two nearly identical tracks are found for one particle). We subtract the remaining continuum contribution with our off-resonance data.

From off-resonance-subtracted like-sign dilepton yields, $N^m(\ell^\pm\ell^\pm)$, we calculate the measured charge asymmetry $a^m_{\ell\ell} \equiv [N^m(\ell^+\ell^+) - N^m(\ell^-\ell^-)]/[N^m(\ell^+\ell^+) + N^m(\ell^-\ell^-)]$, which is related to the desired, corrected asymmetry $a^0_{\ell\ell}$ by

$$a_{\ell\ell}^m = \frac{d_{\ell\ell}^{\text{like}} a_{\ell\ell}^0 + 2a_\eta + r_1(a_{\ell h} + a_f)}{1 + r_1}. \quad (2)$$

Here the dilution $d_{\ell\ell}^{\text{like}}$ is the fraction of like-sign dilepton pairs that are primary pairs, a_η is the charge asymmetry in the efficiency for detecting and identifying leptons, $r_1/(1 + r_1)$ is the fraction of measured like-sign dileptons with one being a misidentified hadron, $a_{\ell h}$ is the asymmetry in like-sign lepton-hadron pairs, and a_f is the asymmetry in the probability that a hadron is misidentified as a lepton. In Eq. (2), pairs with both tracks being hadrons misidentified as leptons and terms that are products of asymmetries are very small compared to the statistical accuracy on $a_{\ell\ell}^m$, and have been neglected. (A note on notation: a superscript m indicates a measured quantity while superscript 0 indicates a true quantity. For example, $a_{\ell\ell}^m$ is the measured like-sign dilepton asymmetry, which is the true asymmetry $a_{\ell\ell}^0$ diluted by backgrounds and possibly biased by false asymmetries. We correct $a_{\ell\ell}^m$ to obtain $a_{\ell\ell}^0$ as described in the text.)

We measure the probability that a pion will be misidentified as a lepton using $\pi^\pm$ tracks from $K_S^0 \to \pi^+\pi^-$ decays and the probability that a kaon will be misidentified as a lepton using $K^\pm$ tracks from $D^{*+} \to \pi^+ D^0 \to \pi^+ K^+ \pi^-$ (and charge conjugate) decays. We combine pion and kaon misidentification probabilities, separately for positive and negative tracks, using the K/π abundance ratio given by Monte Carlo simulation. This procedure gives a probability of 0.9% that a hadron will be misidentified as a muon, 0.04% as a central electron, and 0.3% as a noncentral electron. Using these numbers with the yields of like-sign lepton-hadron pairs, we find values of r_1 ranging from 0.15 ($\mu\mu$) to 0.07 (μe) to 0.006 (ee).

The charge asymmetries in the misidentification probabilities, a_f, are $+0.18 \pm 0.05$ for muons, -0.50 ± 1.00 for central electrons, and $+0.36 \pm 0.25$ for noncentral electrons. The charge asymmetries in like-sign lepton-hadron pairs, $a_{\ell h}$, are small and have small errors ($\sim 0.02 \pm 0.02$). Thus, the correction term $r_1(a_{\ell h} + a_f)$ in Eq. (2) contributes very little to the final uncertainty. In solving Eq. (2) for $a_{\ell\ell}^0$, the term $(1 + r_1)$ multiplies $a_{\ell\ell}^m$. Since the error on $a_{\ell\ell}^m$ is comparable to $a_{\ell\ell}^m$ itself, and since r_1 is reasonably well determined, this correction also contributes little to the final uncertainty.

Dilution factors $d_{\ell\ell}$ are determined from Monte Carlo simulation. For like-sign pairs we find $d_{\ell\ell}^{\text{like}} = 0.70$, while for opposite-sign pairs $d_{\ell\ell}^{\text{opposite}} = 0.96$; for single leptons, the fraction that is primary is $d_\ell = 0.97$. For example, for like-sign lepton pairs 70% of events are primary pairs, 22% are primary-secondary pairs, 7% are events with one primary lepton and one lepton from a J/ψ decay, and 2% are events with a primary lepton and the other lepton from a photon conversion.

This leaves all correction terms in Eq. (2) determined except a_η, the asymmetry in the efficiency for detecting and identifying leptons, positive vs negative. While this asymmetry is not expected to be more than 1%–2%, that is sufficiently large to be important. We see no direct way to measure a_η. Consequently, we turn to the measured asymmetry in yields for single leptons, a_ℓ^m. That asymmetry may be expressed as

$$a_\ell^m = \frac{d_\ell a_\ell^0 + a_\eta + r_0(a_h + a_f)}{1 + r_0}. \quad (3)$$

Here $r_0/(1 + r_0)$ is the ratio of the total yield of misidentified hadrons (total hadron yield times the average misidentification probability) to the total measured lepton yield, a_h is the asymmetry in single hadrons, a_ℓ^0 is related to $a_{\ell\ell}^0$ by Eq. (1), and a_f, a_η, and d_ℓ have been previously defined. We find r_0 equals 0.02 for muons, 0.001 for central electrons, and 0.01 for noncentral electrons. The value of a_f has been previously determined, and a_h is small, with small errors ($\sim 0.01 \pm 0.01$). Thus the correction term $r_0(a_h + a_f)$ contributes little to the final error. Similarly, the factor $(1 + r_0)$ contributes little error. We are thus able to express a_η in terms of a_ℓ^m and $a_{\ell\ell}^0$, and inserting Eq. (3) into Eq. (2), we obtain

$$a_{\ell\ell}^0 = \frac{a_{\ell\ell}^m(1 + r_1) - 2a_\ell^m(1 + r_0) - (r_1 - 2r_0)a_f}{d_{\ell\ell}^{\text{like}} - 2d_\ell \chi_d[f_{00}\tau_0^2/(f_{00}\tau_0^2 + f_{+-}\tau_\pm^2)]}. \quad (4)$$

We have outlined our procedure as if there were only one variety of dilepton pair, while, in fact, there are five: $\mu\mu$, μe, $\mu e'$, ee, and ee', where e and e' refer to central and noncentral electron candidates, respectively. Our actual procedure is to compute a weighted sum of dilepton asymmetries, using Eq. (2), and then eliminate a_η^μ, a_η^e, and $a_\eta^{e'}$ from it using the three measured single lepton asymmetries and Eq. (3). Dilepton yields and asymmetries are given in Table I. Single lepton yields and asymmetries are given in Table II. The combined result is $a_{\ell\ell}^0 = +0.013 \pm 0.050$, where the uncertainty is statistical only.

TABLE I. Yields and asymmetries for dilepton candidates, after subtraction of scaled off-resonance yields.

Sample	++ Yield	−− Yield	Like-sign asymmetry	Opposite-sign yield
$\mu\mu$	286 ± 19	286 ± 19	+0.000 ± 0.046	4395 ± 78
ee	205 ± 17	175 ± 16	+0.079 ± 0.062	3255 ± 64
μe	500 ± 25	505 ± 25	−0.004 ± 0.035	7713 ± 92
$\mu e'$	163 ± 16	126 ± 15	+0.128 ± 0.078	2147 ± 49
ee'	103 ± 19	112 ± 20	−0.042 ± 0.128	1797 ± 59

TABLE II. Yields and asymmetries for single lepton candidates, after subtraction of scaled off-resonance yields.

Sample	+ Yield	− Yield	Asymmetry
μ	$246\,274 \pm 801$	$246\,447 \pm 784$	-0.0004 ± 0.0023
e	$210\,624 \pm 678$	$208\,609 \pm 683$	$+0.0048 \pm 0.0023$
e'	$53\,766 \pm 435$	$53\,731 \pm 440$	$+0.0003 \pm 0.0058$

From the yields of like-sign and opposite-sign dilepton pairs, corrected for misidentified hadrons, we calculate the $B^0\bar{B}^0$ mixing parameter χ_d via

$$\chi_d = \frac{d_{\ell\ell}^{\text{like}}[N(\ell^+\ell^+) + N(\ell^-\ell^-)]}{d_{\ell\ell}^{\text{opposite}}N(\ell^+\ell^-) + d_{\ell\ell}^{\text{like}}[N(\ell^+\ell^+) + N(\ell^-\ell^-)]} \times \left(\frac{f_{00}\tau_0^2 + f_{+-}\tau_\pm^2}{f_{00}\tau_0^2}\right). \quad (5)$$

The dilution-factor-corrected ratio of like-sign to all dilepton pairs in Eq. (5) is consistent among the five varieties of lepton pairs, and averages to 0.081 ± 0.002. The term $[(f_{00}\tau_0^2 + f_{+-}\tau_\pm^2)/f_{00}\tau_0^2]$ corrects the denominator of Eq. (5) for dilepton pairs from B^+B^-. We evaluate it using $f_{+-}\tau_\pm/f_{00}\tau_0 = 1.11 \pm 0.08$ [12] and $\tau_\pm/\tau_0 = 1.06 \pm 0.03$ [13], obtaining 0.46 ± 0.02. This gives $\chi_d = 0.175 \pm 0.008$, to be compared with the Particle Data Group (PDG) value [13] of 0.174 ± 0.009. Note that the value for χ_d that we obtain depends on the correctness of $d_{\ell\ell}^{\text{like}}$. Rather than claim a new measurement of mixing, we turn things around, and use the good agreement with the PDG value to place a limit on the error of $d_{\ell\ell}^{\text{like}}$ of $\pm 7\%$ of itself.

The systematic error of $\pm 7\%$ of $d_{\ell\ell}^{\text{like}}$ leads to a $\pm 9\%$ multiplicative systematic error in $a_{\ell\ell}^0$. Other multiplicative systematic errors considered are from χ_d ($\pm 1.7\%$), and from the off-resonance subtraction ($\pm 1.7\%$). We combine these for an overall multiplicative systematic error of $\pm 10\%$.

We have considered several additive systematic errors, in particular the following sources: imperfect cancellation of a_η between dilepton and single lepton events due to differences in single and dilepton momentum spectra (± 0.0030), systematic uncertainty in the hadron misidentification probability (± 0.0037), difference between a_f for dileptons and a_f for single leptons (small, included in statistical error), systematic uncertainty in the off-resonance subtraction (± 0.0020), and a difference in the momentum scale between positive and negative tracks (± 0.0006). These combine to an additive systematic error of ± 0.005.

In conclusion, we have measured the like-sign dilepton charge asymmetry to be $a_{\ell\ell}^0 = (+0.013 \pm 0.050 \pm 0.005)(1.00 \pm 0.10)$, where the errors are statistical, additive systematic, and multiplicative systematic, respectively. This result is more accurate than our previous dilepton asymmetry measurement [4], $+0.03 \pm 0.10 \pm 0.03$, and supplants it. It is in good agreement with our recent measurement [5] of the $B^0 - \bar{B}^0$ mixing asymmetry via partial hadronic reconstruction, $+0.017 \pm 0.070 \pm 0.014$, and statistically independent of it. We take a weighted average of the two measurements, divide the result by 4, and obtain

$$\frac{\text{Re}(\epsilon_B)}{1 + |\epsilon_B|^2} = +0.0035 \pm 0.0103 \pm 0.0015 .$$

This result is more accurate than CDF's result [6] ($+0.025 \pm 0.062 \pm 0.032$, assuming $\epsilon_{B_s} = 0$) and is of comparable accuracy to OPAL's result [7] ($+0.002 \pm 0.007 \pm 0.003$, assuming $\epsilon_{B_s} = 0$), as well as to a result from ALEPH recently submitted for publication [9]. Furthermore, our result is independent of any assumptions about B_s. It is consistent with zero, and with the standard model predictions, but lacks the statistical accuracy to see asymmetries as small as those predictions. The technique of combining dilepton and single lepton asymmetries to reduce systematic errors will be appropriate for the large data samples soon to be available at B factories.

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