Measurement of Charge Asymmetries in Charmless Hadronic B Meson Decays

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We search for CP-violating charge asymmetries ($\mathcal{A}_{CP}$) in the B meson decays to $K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^{0}$, $K_S^0\pi^{\pm}$, $K^{\pm}\eta'$, and $\omega\pi^{\pm}$. Using 9.66 million $\Upsilon(4S)$ decays collected with the CLEO detector, the statistical precision on $\mathcal{A}_{CP}$ is in the range of ±0.12 to ±0.25 depending on decay mode. While CP-violating asymmetries of up to ±0.5 are possible within the standard model, the measured asymmetries are consistent with zero in all five decay modes studied.

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CP-violating phenomena arise in the standard model because of the single complex parameter in the quark mixing matrix [1]. Such phenomena are expected to occur widely in B meson decays and will be searched for by all current B-physics initiatives in the world. Recent attempts [2] to measure the CP violation parameter $\sin 2\beta$ are tantalizing but statistically limited. There is at the current time no conclusive evidence for CP violation outside the neutral kaon system, where direct CP violation has been recently observed [3].

Direct CP violation, i.e., a difference between the rates for the conjugate decay modes $\bar{B} \to \bar{f}$ and $B \to f$, will occur in any decay mode for which there are two or more contributing amplitudes which differ in both weak and strong phases. This rate difference gives rise to an asymmetry, $\mathcal{A}_{CP}$, defined as

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to \bar{f}) - \mathcal{B}(B \to f)}{\mathcal{B}(\bar{B} \to \bar{f}) + \mathcal{B}(B \to f)}. \quad (1)$$

For the simple case of two amplitudes T, P with $T \ll P$, $\mathcal{A}_{CP}$ is given by

$$\mathcal{A}_{CP} \sim 2\left|\frac{T}{P}\right| \sin\Delta\phi_w \sin\Delta\phi_s. \quad (2)$$

Here $\Delta\phi_s$ and $\Delta\phi_w$ refer to the difference in strong and weak phases between T and P.

The decay $B \to K^{\pm}\pi^{\mp}$, for instance, involves a $b \to u$ W-emission amplitude (T) with the weak phase $\arg(V_{ub}^* V_{us}) \equiv \gamma$ and a $b \to s$ penguin amplitude (P) with the weak phase $\arg(V_{tb}^* V_{ts}) = \pi$ or $\arg(V_{cb}^* V_{cs}) = 0$ [4]. Theoretical expectations of $|T/P| \sim 1/4$ in $B \to K^{\pm}\pi^{\mp}$ [5] thus allow for $\mathcal{A}_{CP}$ as large as ±0.5.

The CP-violating phases may arise from either the standard model CKM matrix or from new physics [6], while the CP-conserving strong phases may arise from the absorptive part of a penguin diagram [7] or from final state interaction effects [8]. Precise predictions for $\mathcal{A}_{CP}$ are not feasible at present as both the absolute value and the strong interaction phases of the contributing amplitudes are not calculable. However, numerical estimates can be made under well-defined model assumptions and the dependence on both model parameters and Cabibbo-Kobayashi-Maskawa (CKM) parameters can be probed. Recent calculations of CP asymmetries under the assumption of factorization have been published by Ali *et al.* [9] and are listed in Table I for the modes examined in this paper. A notable feature of the model used in Ref. [9] is that soft final state interactions are neglected, leading to rather small CP-invariant phases. However, it has been argued recently that CP-conserving phases due to soft rescattering could be large [8], possibly leading to enhanced $|\mathcal{A}_{CP}|$ [10].

In this Letter, we present results of searches for CP violation in decays of B mesons to the three $K\pi$ modes, $K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^{0}$, $K_S^0\pi^{\pm}$, the mode $K^{\pm}\eta'$, and the vector-pseudoscalar mode $\omega\pi^{\pm}$. These decay modes are selected because they have well-measured branching ratios and significant signal yields in our data sample [11]. In addition, these decays are self-tagging; the flavor of the parent b or $\bar{b}$ quark is tagged simply by the sign of the high momentum charged hadron. In the decay $B \to K^{\pm}\pi^{\mp}$ we assume that the charge of the kaon tags the charge of the b quark.

The data used in this analysis were collected with two configurations of the CLEO detector at the Cornell Electron Storage Ring (CESR). It consists of an integrated luminosity of 9.13 fb^{-1} taken on the Υ(4S) resonance, corresponding to 9.66×10^6 $B\bar{B}$ pairs, and 4.35 fb^{-1} taken below $B\bar{B}$ threshold, used for continuum background studies. CLEO is a general purpose solenoidal magnet detector, described in detail elsewhere [12]. Cylindrical drift chambers in a 1.5 T solenoidal magnetic field measure momenta and specific ionization (dE/dx) of charged tracks. Photons are detected using a 7800-crystal CsI(Tl) electromagnetic calorimeter. For the second configuration, the innermost tracking chamber was replaced by a three-layer, double-sided silicon vertex detector, and the gas in the main

TABLE I. Summary of results. Signal yields are taken from Ref. [11]. Theory predictions are from Ref. [9], and include only standard model perturbative calculations. The 90% C.L. interval includes statistical and systematic errors (±0.02) added in quadrature.

Mode	Signal yield	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$ 90% C.L.	$\mathcal{A}_{CP}$ theory
$K^{\pm}\pi^{\mp}$	80^{+12}_{-11}	-0.04 ± 0.16	$[-0.30, 0.22]$	$(+0.037, +0.106)$
$K^{\pm}\pi^{0}$	$42.1^{+10.9}_{-9.9}$	-0.29 ± 0.23	$[-0.67, 0.09]$	$(+0.026, +0.092)$
$K_S^0\pi^{\pm}$	$25.2^{+6.4}_{-5.6}$	$+0.18 \pm 0.24$	$[-0.22, 0.56]$	$(0.014, +0.018)$
$K^{\pm}\eta'$	100^{+13}_{-12}	$+0.03 \pm 0.12$	$[-0.17, 0.23]$	$(+0.020, +0.061)$
$\omega\pi^{\pm}$	$28.5^{+8.2}_{-7.3}$	-0.34 ± 0.25	$[-0.75, 0.07]$	$(-0.120, +0.024)$

drift chamber was changed from an argon-ethane to a helium-propane mixture. These modifications led to improved dE/dx resolution in the main drift chamber, as well as improved momentum resolution. Two-thirds of the data used in the present analysis were taken with the improved detector configuration.

Efficient track quality requirements are imposed on charged tracks. Pions and kaons are identified by dE/dx. The separation between kaons and pions for typical signal momenta $p \sim 2.6$ GeV/c is 1.7 and 2.0 standard deviations (σ) for the two detector configurations. Candidate K_S^0 are selected from pairs of tracks forming well-measured displaced vertices with a $\pi^+\pi^-$ invariant mass within 2σ of the K_S^0 mass. Pairs of photons with an invariant mass within 2.5σ of the nominal π^0 mass are kinematically fitted with the mass constrained to the nominal π^0 mass. For the high momentum K_S^0 and π^0 candidates reconstructed with these requirements, the ratio of signal to combinatoric background is better than 10. Electrons are rejected based on dE/dx and the ratio of the track momentum to the associated shower energy in the CsI calorimeter; muons are rejected based on the penetration depth in the instrumented steel flux return. Resonances are reconstructed through the decay channels $\eta' \to \eta\pi^+\pi^-$ with $\eta \to \gamma\gamma$, $\eta' \to \rho\gamma$ with $\rho \to \pi^+\pi^-$, and $\omega \to \pi^+\pi^-\pi^0$.

The $\mathcal{A}_{CP}$ analyses presented here are closely related to the corresponding branching fraction determinations published elsewhere [11]. We briefly summarize here the main points of the analysis.

We calculate a beam-constrained B mass $M = \sqrt{E_b^2 - p_B^2}$, where p_B is the B candidate momentum and E_b is the beam energy. The resolution in M ranges from 2.5 to 3.0 MeV, where the larger resolution corresponds to the $B^\pm \to K^\pm\pi^0$ decay. We define $\Delta E = E_1 + E_2 - E_b$, where E_1 and E_2 are the energies of the daughters of the B meson candidate. The resolution on ΔE is mode dependent. For final states without photons, the ΔE resolutions for the two configurations of the CLEO detector are 26 and 20 MeV. We accept candidates with M within 5.2–5.3 GeV and $|\Delta E| < 200$ MeV, and extract yields and asymmetries with an unbinned maximum likelihood fit. The fiducial region in M and ΔE includes the signal region and a substantial sideband for background determination. Sideband regions are also included around each of the resonance masses (η', η, and ω) for use in the likelihood fit. For the $\eta' \to \rho\gamma$ case, the ρ mass is not included in the fit; we require 0.5 GeV $< m_{\pi\pi} <$ 0.9 GeV.

The main background arises from $e^+e^- \to q\bar{q}$ (where $q = u, d, s, c$). Such events typically exhibit a two-jet structure and can produce high momentum back-to-back tracks in the fiducial region. To reduce contamination from these events, we calculate the angle θ_s between the sphericity axis [13] of the candidate tracks and showers and the sphericity axis of the rest of the event. The distribution of $\cos\theta_s$ is strongly peaked at ±1 for $q\bar{q}$ events and is nearly flat for $B\bar{B}$ events. For $K\pi$ modes, we require $|\cos\theta_s| < 0.8$ which eliminates 83% of the background. For η' and ω modes, the requirement is $|\cos\theta_s| < 0.9$. detail in Ref. [14]. Additional discrimination between signal and $q\bar{q}$ background is obtained from event shape information used in a Fisher discriminant ($\mathcal{F}$) technique as described in detail in Ref. [14].

Using a detailed GEANT-based Monte Carlo simulation [15] we determine overall detection efficiencies of 0.48 ($K^\pm\pi^\mp$), 0.38 ($K^\pm\pi^0$), 0.15 ($K^0\pi^\pm$), 0.13 ($K^\pm\eta'$), and 0.26 ($\omega\pi^\pm$). These efficiencies include secondary branching fractions for $K^0 \to K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$ as well as for the η' and ω decay modes where applicable.

To extract signal and background yields we perform unbinned maximum-likelihood fits using ΔE, M, $\mathcal{F}$, $|\cos\theta_B|$ (if not used in $\mathcal{F}$), dE/dx, daughter resonance mass, and helicity angle in the daughter decay. The free parameters to be fitted are the asymmetry $(\bar{f} - f)/(\bar{f} + f)$ and the sum $(\bar{f} + f)$ in both signal and background. In most cases there is more than one possible signal hypothesis and its corresponding background hypothesis, e.g., we fit simultaneously for $K^\pm\pi^0$ and $\pi^\pm\pi^0$ to ensure proper handling of the K/π identification information. The probability density functions (PDFs) describing the distribution of events in each variable are parametrized by simple forms (Gaussian, polynomial, etc.) whose parameters are determined in separate studies. For signal PDF shapes parameters are determined by fitting simulated signal events. Backgrounds in these analyses are dominated by continuum $e^+e^- \to q\bar{q}$ events, and we determine parameters of the background PDFs by fitting data collected below the $\Upsilon(4S)$ resonance. The uncertainties associated with such fits are charge symmetric in all PDFs except the dE/dx parametrization. The dE/dx information was calibrated such that any residual charge asymmetry is negligible compared to the statistical errors for $\mathcal{A}_{CP}$.

The experimental determination of charge asymmetries in this analysis depends entirely on the properties of high momentum tracks. The charged meson that tags the parent $b/\bar{b}$ flavor has in each case a momentum between 2.3 and 2.8 GeV/c. In independent studies, using very large samples of high momentum tracks, we searched for and set stringent limits on the extent of possible charge-correlated bias in the CLEO detector and analysis chain for tracks in the 2–3 GeV/c momentum range. Based on a sample of 8×10^6 tracks, we find an $\mathcal{A}_{CP}$ bias of less than ±0.002 introduced by differences in reconstruction efficiencies for positive and negative high momentum tracks.

For $K^\pm\pi^\mp$ combinations, where differential charge-correlated efficiencies must also be considered in correlation with K/π flavor, we use 37 000 $D^0 \to K\pi(\pi^0)$ decays and set a limit on the $\mathcal{A}_{CP}$ bias of ±0.005. These D^0 meson decays, together with an additional 24 000 $D_{(s)}^\pm$ meson decays, are also used to set an upper limit of 0.4 MeV/c on any charge-correlated or charge-strangeness-correlated bias in the momentum measurement. The resulting limit on $\mathcal{A}_{CP}$ bias from this source is ± 0.002. We conclude that there is no significant $\mathcal{A}_{CP}$ bias introduced by track reconstruction or selection.

Our ability to distinguish the final states $K^+\pi^-$ and $K^-\pi^+$ depends entirely on particle identification using dE/dx. In addition, all other decay modes depend to varying degrees on dE/dx to distinguish between $B \to X\pi^+$ and XK^+, X being a K_S^0, π^0, η', or an ω. The dE/dx was carefully calibrated in order to remove any possible charge dependencies.

We calibrate the dE/dx response using radiative μ pair events assuming that for a given velocity dE/dx is the same for $\mu^\pm$, $\pi^\pm$, and $K^\pm$. We then compare the dE/dx response for positive and negative tracks in the momentum range 2–3 GeV/c from all hadronic events in the CLEO data sample. The large available statistics allows us to split the data into subsets and to verify the stability of the calibration over time. The fully calibrated dE/dx is then verified using kinematically identified kaons and pions of 2–3 GeV/c from $D^0 \to K\pi(\pi^0)$ decays. The dE/dx distributions for $K^\pm$ and $\pi^\pm$ from this sample are shown in Fig. 1. No significant differences are seen between different charge species. The statistical uncertainty in this comparison translates into a possible $\mathcal{A}_{CP}$ bias of ± 0.01 for $K^\pm\pi^\mp$, and less for all other final states. We conservatively assign a total systematic error of ± 0.02 in all five decay modes.

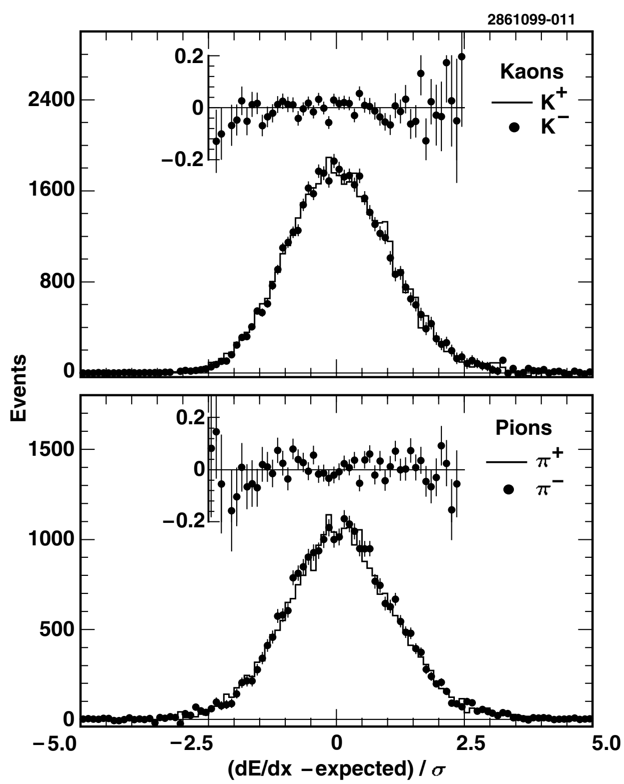

FIG. 1. Comparison of normalized dE/dx distributions for K^+ and K^- (above); and π^+ and π^- (below). The inset shows the asymmetry $(K^- - K^+)/(K^- + K^+)$ and $(\pi^- - \pi^+)/(\pi^- + \pi^+)$, respectively. Kinematically identified kaons and pions of momenta 2–3 GeV/c from $D^0 \to K\pi(\pi^0)$ decays in data are used for this comparison.

As an additional check we measure the asymmetry of the background events in each decay mode, and find that all are consistent with the expected null result for continuum background. The results for the asymmetry in the continuum background are -0.024 ± 0.038 $(K^\pm\pi^\mp)$, -0.003 ± 0.032 $(K^\pm\pi^0)$, -0.017 ± 0.037 $(K_S^0\pi^\pm)$, -0.006 ± 0.070 $[\eta'(\eta\pi\pi)K^\pm]$, -0.009 ± 0.015 $[\eta'(\rho\gamma)K^\pm]$, and -0.001 ± 0.010 $(\omega\pi^\pm)$. We further confirm that our analysis method does not introduce a bias in the measured $\mathcal{A}_{CP}$ in the analysis of simulated events with known asymmetries.

We conclude that any possible systematic bias on $\mathcal{A}_{CP}$ is negligible compared to the statistical errors of our measurements. Our 90% confidence level (C.L.) ranges are calculated adding statistical and systematic errors in quadrature.

We summarize the results in Table I and Fig. 2. The dependence of the likelihood function on $\mathcal{A}_{CP}$ for each of the five decay modes is depicted in Fig. 3. This figure was obtained by reoptimizing the likelihood function at each fixed value of $\mathcal{A}_{CP}$ to account for correlations between the free parameters in the fit.

We see no evidence for CP violation in the five modes analyzed here and set 90% C.L. intervals that reduce the possible range of $\mathcal{A}_{CP}$ by as much as a factor of 4. It has been suggested [16] that $\mathcal{A}_{CP}$ in $K^\pm\pi^\mp$ and $K^\pm\pi^0$ are expected to be almost identical within the standard model. Based on the average $\mathcal{A}_{CP}$ in these two decay modes we calculate a 90% C.L. range of $-0.28 < \mathcal{A}_{CP} < +0.05$.

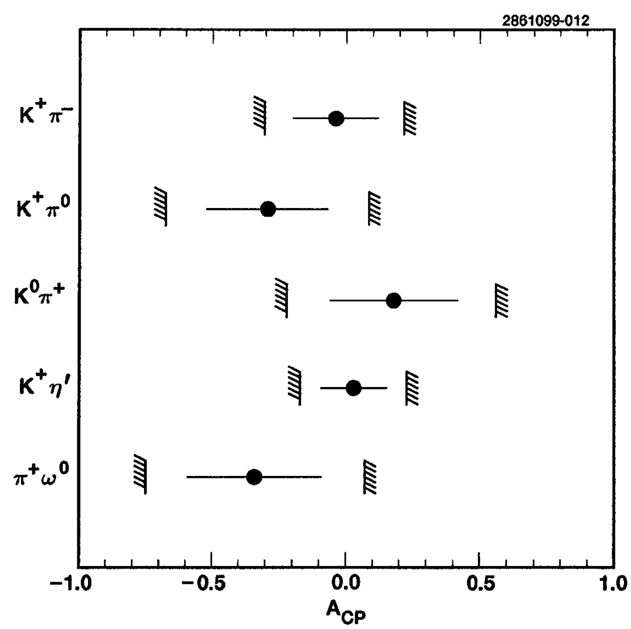

FIG. 2. $\mathcal{A}_{CP}$ measurements. Error bars include systematics; hatched regions delimit the 90% C.L. intervals.

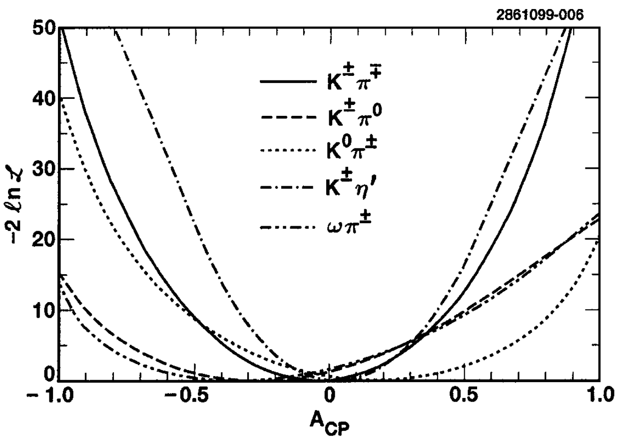

FIG. 3. Likelihood function ($-2\ln\mathcal{L}$) versus $\mathcal{A}_{CP}$ for each of the five modes.

While the sensitivity is not yet sufficient to probe the rather small $\mathcal{A}_{CP}$ values predicted by factorization models, extremely large $\mathcal{A}_{CP}$ values that might arise if large strong phase differences were available from final state interactions are firmly ruled out. For the cases of $K\pi$ and $\eta' K$, we can exclude $|\mathcal{A}_{CP}|$ greater than 0.30 and 0.23 at 90% C.L., respectively.

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