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Measurements of CP-Violating Asymmetries and Branching Fractions in B Decays to ωK and $\omega\pi$

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We present measurements of *CP*-violating asymmetries and branching fractions for the decays $B^+ \to \omega\pi^+$, $B^+ \to \omega K^+$, and $B^0 \to \omega K^0$. The data sample corresponds to 232 million $B\overline{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$ resonance. For the decay $B^0 \to \omega K^0_S$, we measure the time-dependent *CP*-violation parameters $S = 0.51^{+0.35}_{-0.39} \pm 0.02$, and $C = -0.55^{+0.28}_{-0.26} \pm 0.03$. We also measure the branching fractions, in units of 10^{-6}, $\mathcal{B}(B^+ \to \omega\pi^+) = 6.1 \pm 0.7 \pm 0.4$, $\mathcal{B}(B^+ \to \omega K^+) = 6.1 \pm 0.6 \pm 0.4$, and $\mathcal{B}(B^0 \to \omega K^0) = 6.2 \pm 1.0 \pm 0.4$, and charge asymmetries $\mathcal{A}_{ch}(B^+ \to \omega\pi^+) = -0.01 \pm 0.10 \pm 0.01$ and $\mathcal{A}_{ch}(B^+ \to \omega K^+) = 0.05 \pm 0.09 \pm 0.01$.

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Measurements of time-dependent *CP* asymmetries in B^0 meson decays through a Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitude [1, 2] have firmly established that *CP* is not conserved in such decays. The effect, arising from the interference between mixing and decay involving the *CP*-violating phase $\beta = \arg\left(-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right)$ of the CKM mixing matrix [3], manifests itself as an asymmetry in the time evolution of the $B^0\overline{B}^0$ pair.

Decays to the charmless final states ϕK^0, $K^+K^-K^0_S$, $\eta' K^0$, $\pi^0 K^0$, $f_0(980)K^0$, and ωK^0 are all $b \to q\bar{q}s$ processes dominated by a single penguin (loop) amplitude having the same weak phase β [4]. CKM-suppressed amplitudes and multiple particles in the loop complicate the situation by introducing other weak phases whose contributions are not negligible; see Refs. [5, 6] for early quantitative work in addressing the size of these effects. We define ΔS as the difference between the time-dependent *CP*-violating parameter S (given in detail below) measured in these decays and $S = \sin 2\beta$ measured in charmonium K^0 decays. For the decay $B^0 \to \omega K^0$, these additional contributions are expected to give $\Delta S \sim 0.1$ [7, 8], although this increase may be nullified when final-state interactions are included [8]. A value of ΔS inconsistent with this expectation could be an indication of new physics [9].

We present an improved measurement of the time-dependent *CP*-violating asymmetry in the decay $B^0 \to \omega K^0$, previously reported by the Belle Collaboration based on a sample of $\sim$30 events [10]. We also measure branching fractions for the decays $B^0 \to \omega K^0$, $B^+ \to \omega\pi^+$, and $B^+ \to \omega K^+$ (charge-conjugate decay modes are implied throughout), and for $B^+ \to \omega\pi^+$, and $B^+ \to \omega K^+$, we measure the time-integrated charge asymmetry $\mathcal{A}_{ch} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where $\Gamma^\pm$ is the width for these charged decay modes. In the Standard Model $\mathcal{A}_{ch}$ is expected to be consistent with zero within our experimental uncertainty; a non-zero value would indicate direct *CP* violation in this channel.

The data were collected with the *BABAR* detector [11] at the PEP-II asymmetric e^+e^- collider. An integrated luminosity of 211 fb^{-1}, corresponding to 232 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double-sided detectors, and a 40-layer central drift chamber, both operating in a 1.5 T axial magnetic field. Charged-particle identification (PID) is provided by the energy loss in the tracking devices and by the measured Cherenkov angle from an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A K/π separation of better than four standard deviations (σ) is achieved for momenta below 3 GeV/c, decreasing to 2.5σ at the highest momenta in the B decay final states. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter.

From a $B^0\overline{B}^0$ pair produced in an $\Upsilon(4S)$ decay, we reconstruct one of the B mesons in the final state $f = \omega K^0_S$, a *CP* eigenstate with eigenvalue -1. For the time evolution measurement, we also identify (tag) the flavor (B^0 or $\overline{B}^0$) and reconstruct the decay vertex of the other B. The asymmetric beam configuration in the laboratory frame provides a boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$, which allows the determination of the proper decay time difference $\Delta t \equiv t_f - t_{\rm tag}$ from the vertex separation of the two B meson candidates. Ignoring the Δt resolution (about 0.5 ps), the distribution of Δt is

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1-2w)\left(S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right)]. \tag{1}$$

The upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 ($\overline{B}^0$) meson is tagged as a $\overline{B}^0$ (B^0). The parameter C measures direct *CP* violation. If $C = 0$, then $S = \sin 2\beta + \Delta S$.

The flavor-tagging algorithm [1] has seven mutually exclusive tagging categories of differing purities (including one for untagged events that we retain for yield determinations). The measured analyzing power, defined as efficiency times $(1-2w)^2$ summed over all categories, is

$(30.5 \pm 0.6)\%$, as determined from a large sample of B-decays to fully reconstructed flavor eigenstates ($B_{\rm flav}$).

We reconstruct a B meson candidate by combining a π^+, K^+ or K^0_S with an $\omega \to \pi^+\pi^-\pi^0$. We select $K^0_S \to \pi^+\pi^-$ decays by requiring the $\pi^+\pi^-$ invariant mass to be within 12 MeV of the nominal K^0 mass and by requiring a flight length greater than three times its error. We require the $\pi^+\pi^-\pi^0$ invariant mass ($m_{3\pi}$) to be between 735 and 825 MeV. Distributions from the data and from Monte Carlo (MC) simulations [12] guide the choice of these selection criteria. We retain regions adequate to characterize the background as well as the signal for those quantities taken subsequently as observables for fitting. We also use in the fit the angle θ_H, defined, in the ω rest frame, as the angle of the direction of the boost from the B rest frame with respect to the normal to the ω decay plane. The quantity $\mathcal{H} \equiv |\cos\theta_H|$ is approximately flat for background and distributed as $\cos^2\theta_H$ for signal.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0\cdot\mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where $(E_0, \mathbf{p}_0)$ and $(E_B, \mathbf{p}_B)$ are four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. We require, assuming the $B^+ \to \omega\pi^+$ hypothesis, $|\Delta E| \leq 0.2$ GeV and $5.25 \leq m_{\rm ES} \leq 5.29$ GeV.

To reject the dominant background from continuum $e^+e^- \to q\overline{q}$ events ($q = u, d, s, c$), we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the $\Upsilon(4S)$ rest frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for jet-like $q\overline{q}$ pairs and is nearly uniform for the isotropic B decays; we require $|\cos\theta_T| < 0.9$ (0.8 for the charged B decays).

From MC simulations of $B^0\overline{B}^0$ and B^+B^- events, we find evidence for a small (0.5%) $B\overline{B}$ background contribution for the charged B decays, so we have added a $B\overline{B}$ component to the fit described below for those channels.

We use an unbinned, multivariate maximum-likelihood fit to extract signal yields and CP-violation parameters. We use the discriminating variables $m_{\rm ES}$, ΔE, $m_{3\pi}$, $\mathcal{H}$, and a Fisher discriminant $\mathcal{F}$ [13]. The Fisher discriminant combines five variables: the polar angles with respect to the beam axis in the $\Upsilon(4S)$ frame of the B candidate momentum and of the B thrust axis; the tagging category; and the zeroth and second angular moments of the energy flow, excluding the B candidate, about the B thrust axis [13]. We also use Δt for the $B^0 \to \omega K^0_S$ decay, while for the charged B decays we use the PID variables T_π and T_K, defined as the number of standard deviations between the measured DIRC Cherenkov angle and that expected for pions and kaons, respectively.

For the $B^0 \to \omega K^0_S$ decay we define the probability density function (PDF) for each event i, hypothesis j (signal and $q\overline{q}$ background), and tagging category c

$$\begin{aligned}\mathcal{P}^i_{j,c} \;\equiv\; & \mathcal{P}_j(m_{\rm ES}{}^i)\mathcal{P}_j(\Delta E^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(m^i_{3\pi}) \\ & \mathcal{P}_j(\mathcal{H}^i)\mathcal{P}_j(\Delta t^i, \sigma^i_{\Delta t}, c)\,,\end{aligned} \qquad (2)$$

where $\sigma^i_{\Delta t}$ is the error on Δt for event i. We write the extended likelihood function as

$$\mathcal{L} = \prod_c \exp{(-\sum_j Y_j f_{j,c})} \prod_i^{N_c} \left[\sum_j Y_j f_{j,c} \mathcal{P}^i_{j,c}\right]\,, \qquad (3)$$

where Y_j is the fit yield of events of species j, $f_{j,c}$ is the fraction of events of species j for each category c, and N_c is the number of events of category c in the sample. We fix $f_{{\rm sig},c}$ to $f_{B_{\rm flav},c}$, the values measured with the large $B_{\rm flav}$ sample [1]. The same likelihood function is used for the charged decays except that the hypothesis j also includes $B\overline{B}$ background, the tagging category is not used and the PDF is slightly different, involving flavor k (primary π^+ or K^+):

$$\mathcal{P}^i_{jk} = \mathcal{P}_j(m_{\rm ES}{}^i)\mathcal{P}_j(\Delta E^i_k, T^i_k)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(m^i_{3\pi})\mathcal{P}_j(\mathcal{H}^i)\,. \qquad (4)$$

The PDF $\mathcal{P}_{\rm sig}(\Delta t, \sigma_{\Delta t}, c)$, is the convolution of $F(\Delta t; c)$ (Eq. 1) with the signal resolution function (a sum of three Gaussians) determined from the $B_{\rm flav}$ sample. The other PDF forms are: the sum of two Gaussians for all signal shapes except $\mathcal{H}$, and the peaking component of the $m_{3\pi}$ background; the sum of three Gaussians for $\mathcal{P}_{q\overline{q}}(\Delta t; c)$; an asymmetric Gaussian with different widths below and above the peak for $\mathcal{P}_j(\mathcal{F})$ (a small "tail" Gaussian is added for $\mathcal{P}_{q\overline{q}}(\mathcal{F})$); Chebyshev functions of second to fourth order for $\mathcal{H}$ signal and the slowly-varying shapes of ΔE, $m_{3\pi}$, and $\mathcal{H}$ backgrounds; and, for $\mathcal{P}_{q\overline{q}}(m_{\rm ES})$, a phase-space-motivated empirical function [14], with a small Gaussian added for $\mathcal{P}_{B\overline{B}}(m_{\rm ES})$.

We determine the PDF parameters from simulation for the signal and $B\overline{B}$ background components. We study large control samples of $B \to D\pi$ decays of similar topology to verify the simulated resolutions in ΔE and $m_{\rm ES}$, adjusting the PDFs to account for any differences found. For the $q\overline{q}$ background we use $(m_{\rm ES}, \Delta E)$ sideband data to obtain initial PDF-parameter values but ultimately leave them free to vary in the final fit.

We compute the branching fractions and charge asymmetry from fits performed without Δt or flavor tagging. The free fit parameters are the following: the signal and $q\overline{q}$ background yields (the $B\overline{B}$ yield, if present, is fixed); the three shape parameters of $\mathcal{P}_{q\overline{q}}(\mathcal{F})$; the slope of $\mathcal{P}_{q\overline{q}}(\Delta E)$ and $\mathcal{P}_{q\overline{q}}(m_{3\pi})$; the fraction of the peaking component of $\mathcal{P}_{q\overline{q}}(m_{3\pi})$; ξ [14]; and, for the charged B decays, the signal and background $\mathcal{A}_{ch}$.

Table I lists the quantities used to determine the branching fraction. Equal production rates of B^+B^- and $B^0\overline{B}^0$ pairs have been assumed. Small yield biases

TABLE I: Fit sample size, signal yield, estimated yield bias (all in events) , estimated purity, detection efficiency, daughter branching fraction product, statistical significance including systematic errors, measured branching fraction, and corrected signal charge asymmetry.

Quantity	$\omega\pi^+$	ωK^+	ωK^0
Events in fit	44175		9145
Signal yield	274 ± 28	266 ± 24	100 ± 15
Yield bias	18	16	8
Purity (%)	34	46	46
Eff. (ϵ,%)	21.8	21.2	23.0
$\prod \mathcal{B}_i$	0.891	0.891	0.307
$\epsilon \times \prod \mathcal{B}_i$ (%)	18.2	17.7	6.4
Significance (σ)	10.8	13.0	8.6
$\mathcal{B}(10^{-6})$	6.1 ± 0.7	6.1 ± 0.6	6.2 ± 1.0
Signal $\mathcal{A}_{ch}$	-0.01 ± 0.10	0.05 ± 0.09	–

are present in the fit, due primarily to unmodeled correlations among the signal PDF parameters. In Table I we include estimates of these biases, evaluated by fitting simulated $q\overline{q}$ experiments drawn from the PDF into which we have embedded the expected number of signal and $B\overline{B}$ background events randomly extracted from the fully simulated MC samples. The estimated purity in Table I is given by the ratio of the signal yield to the effective background plus signal, the latter being defined as the square of the error on the yield.

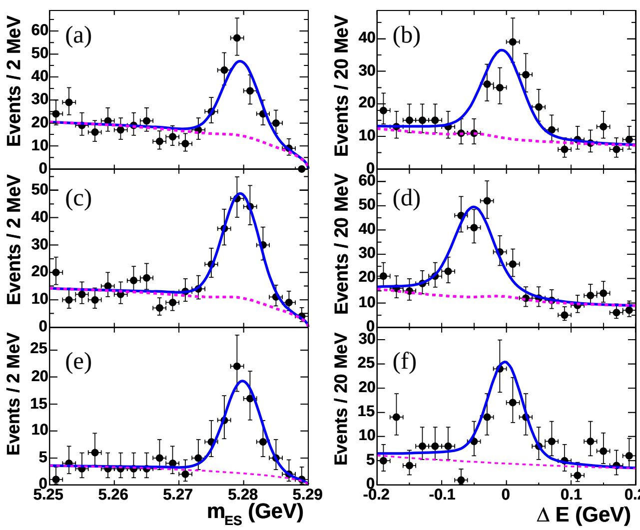

FIG. 1: The B candidate $m_{\rm ES}$ and ΔE projections for $B^+ \to \omega\pi^+$ (a, b), $B^+ \to \omega K^+$ (c, d), and $B^0 \to \omega K^0$ (e, f) shown for a signal-enhanced subset of the data. Points with error bars represent the data, the solid line the fit function, and the dashed line the background components. Note that the ωK^+ signal in the ΔE plot is displaced from zero since ΔE is defined for the $\omega\pi^+$ hypothesis.

Fig. 1 shows projections onto $m_{\rm ES}$ and ΔE for a subset of the data (including 45–65% of signal events) for which the signal likelihood (computed without the variable plotted) exceeds a threshold that optimizes the sensitivity.

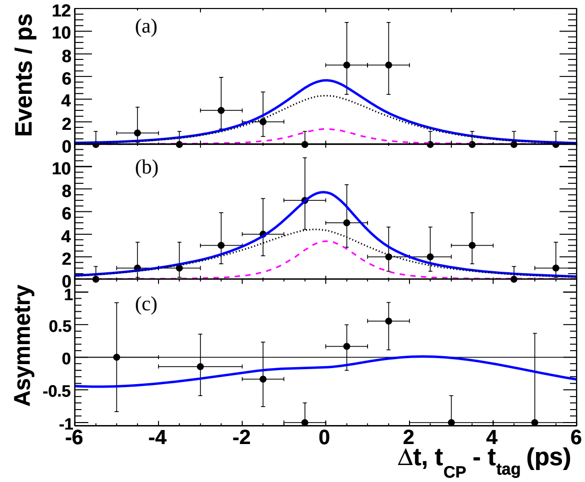

FIG. 2: Projections onto Δt for $B^0 \to \omega K^0$. Data (points with errors), the fit function (solid line), background component (dashed line), and signal component (dotted line), for events in which the tag meson is (a) B^0 and (b) $\overline{B}^0$, and (c) the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$.

For the time-dependent analysis, we require $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps. The free parameters in the fit are the same as for the branching fraction fit plus S, C, the fraction of background events in each tagging category, and the six primary parameters describing the Δt background shape. The parameters τ and Δm_d are fixed to world-average values [15]. Here we find a slightly smaller yield of 95±14 events and $S = 0.51^{+0.35}_{-0.39}$, $C = -0.55^{+0.28}_{-0.26}$. The errors have been scaled by ∼1.10 to account for a slight underestimate of the fit errors predicted by our simulations when the signal sample size is small. Fig. 2 shows the Δt projections and asymmetry of the time-dependent fit with events selected as for Fig. 1.

The major systematic uncertainties affecting the branching fraction measurements include the reconstruction efficiency (0.8% per charged track, 1.5% per photon, and 2.1% per K^0_S) estimated from auxiliary studies. We take one-half of the measured yield bias (3–4%) as a systematic error. The uncertainty due to the signal PDF description is estimated to be $\lesssim 1\%$ in studies where the signal PDF parameters are varied within their estimated errors. The uncertainty due to $B\overline{B}$ background is also estimated to be 1% by variation of the fixed $B\overline{B}$ yield by its estimated uncertainty. The $\mathcal{A}_{ch}$ bias is estimated to be -0.005 ± 0.010 from studies of signal MC, control samples, and calculation of the asymmetry due to particles interacting in the detector. We correct for this bias and assign a systematic uncertainty of 0.01 for $\mathcal{A}_{ch}$ for both $B^+ \to \omega\pi^+$ and $B^+ \to \omega K^+$.

For the time-dependent measurements, we estimate systematic uncertainties in S and C due to $B\overline{B}$ background and PDF shape variation (0.01 each), modeling of the signal Δt distribution (0.02), and interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [16] (0.02 for C, negligible for S). We also find that the uncertainty due to SVT alignment and position and size of the beam spot are negligible. The $B_{\rm flav}$ sample is used to determine the errors associated with the signal PDF parameters: Δt resolutions, tagging efficiencies, and mistag rates; published measurements [15] are used for τ_B and Δm_d. Summing all systematic errors in quadrature, we obtain 0.02 for S and 0.03 for C.

In conclusion, we have measured the branching fractions and time-integrated charge asymmetry for the decays $B^+ \to \omega\pi^+$ and $B^+ \to \omega K^+$ and the branching fraction for $B^0 \to \omega K^0$. We find $\mathcal{B}(B^+ \to \omega\pi^+) = (6.1 \pm 0.7 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \to \omega K^+) = (6.1 \pm 0.6 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^0 \to \omega K^0) = (6.2 \pm 1.0 \pm 0.4) \times 10^{-6}$, $\mathcal{A}_{ch}(B^+ \to \omega\pi^+) = -0.01 \pm 0.10 \pm 0.01$, and $\mathcal{A}_{ch}(B^+ \to \omega K^+) = 0.05 \pm 0.09 \pm 0.01$, where the first errors are statistical and the second systematic. These results are substantially more precise than earlier measurements [17] and a significant improvement over our previous measurements [18], which they supersede. We also measure the time-dependent asymmetry parameters for the decay $B^0 \to \omega K^0$, $S = 0.51^{+0.35}_{-0.39} \pm 0.02$ and $C = -0.55^{+0.28}_{-0.26} \pm 0.03$, with a precision nearly a factor of two better than the previous Belle Collaboration results [10]. If we fix $C = 0$, we find $S = 0.60^{+0.42}_{-0.38}$. This value of S and the world-average value of sin2β [1, 2] yield a value of $\Delta S = 0.12 \pm 0.40$, in good agreement with the expected value near zero.

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