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Measurements of $CP$-violating asymmetries and branching fractions in $B$ decays to $\omega K$ and $\omega\pi$


$B_{s}^{0}\rightarrow\pi^{0}\pi^{0}$ decays to $\omega K$ and $\omega\pi$
MEASUREMENTS OF CP-VIOLATING ASYMMETRIES... PHYSICAL REVIEW D 74, 011106(R) (2006)

25 Ecole Polytechnique, LLR, F-91128 Palaiseau, France
26 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
27 Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
28 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29 Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
30 Harvard University, Cambridge, Massachusetts 02138, USA
31 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
32 Imperial College London, London, SW7 2AZ, United Kingdom
33 University of Iowa, Iowa City, Iowa 52242, USA
34 Iowa State University, Ames, Iowa 50011-3160, USA
35 Johns Hopkins Univ. Dept of Physics & Astronomy 3400 N. Charles Street Baltimore, Maryland 21218, USA
36 Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
37 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 ORSAY Cedex, France
38 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
39 University of Liverpool, Liverpool L69 7ZE, United Kingdom
40 Queen Mary, University of London, E1 4NS, United Kingdom
41 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
42 University of Louisville, Louisville, Kentucky 40292, USA
43 University of Manchester, Manchester M13 9PL, United Kingdom
44 University of Maryland, College Park, Maryland 20742, USA
45 University of Massachusetts, Amherst, Massachusetts 01003, USA
46 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
47 McGill University, Montréal, Québec, Canada H3A 2T8
48 Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
49 University of Mississippi, University, Mississippi 38677, USA
50 Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
51 Mount Holyoke College, South Hadley, Massachusetts 01075, USA
52 Università di Napoli Federico II, Dipartimento di Scienze Fisiche e INFN, I-80126, Napoli, Italy
53 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
54 University of Notre Dame, Notre Dame, Indiana 46556, USA
55 Ohio State University, Columbus, Ohio 43210, USA
56 University of Oregon, Eugene, Oregon 97403, USA
57 Università di Padova, Dipartimento di Fisica e INFN, I-35131 Padova, Italy
58 Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France
59 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
60 Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
61 Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
62 Prairie View A&M University, Prairie View, Texas 77446, USA
63 Princeton University, Princeton, New Jersey 08544, USA
64 Università di Roma La Sapienza, Dipartimento di Fisica e INFN, I-00185 Roma, Italy
65 Universität Rostock, D-18051 Rostock, Germany
66 Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
67 DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
68 University of South Carolina, Columbia, South Carolina 29208, USA
69 Stanford Linear Accelerator Center, Stanford, California 94309, USA
70 Stanford University, Stanford, California 94305-4060, USA
71 State University of New York, Albany, New York 12222, USA
72 University of Tennessee, Knoxville, Tennessee 37996, USA
73 University of Texas at Austin, Austin, Texas 78712, USA
74 University of Texas at Dallas, Richardson, Texas 75083, USA
75 Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
76 Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
77 IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
78 University of Victoria, Victoria, British Columbia, Canada V8W 3P6
79 Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

*Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France
†Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡Also with Università della Basilicata, Potenza, Italy

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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 $232 \times 10^6 \bar{B}B$ pairs produced by $e^+e^-$ annihilation at the $\Upsilon(4S)$ resonance. For the decay $B^0 \to \omega K^0$, we measure the time-dependent CP-violation parameters $S = 0.51^{+0.35}_{-0.26} \pm 0.02$, 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 $A_{cb}(B^+ \to \omega \pi^+) = -0.01 \pm 0.10 \pm 0.01$ and $A_{cb}(B^+ \to \omega K^+) = 0.05 \pm 0.09 \pm 0.01$.

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 $\beta = \arg(-V_{cd}V_{cb}^*/V_{ud}V_{ub}^*)$ of the CKM mixing matrix [3], manifests itself as an asymmetry in the time evolution of the $B^0\bar{B}^0$ pair. Decays to the charmedless final states $f'K^0, K^+K^-K^0, \eta'K^0, \pi^0K^0, f_0(980)K^0$, and $\omega K^0$ are all $b \to q\bar{q}s$ processes dominated by a single penguin (loop) amplitude having the same weak phase $\beta$ [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 $\Delta S$ as the difference between the time-dependent CP-violating parameter $S$ (given in detail below) measured in these decays and $S = \sin2\beta$ 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 $\Delta S$ 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 $\tilde{A}_{cb} = (\Gamma^- - \Gamma^+)/(|\Gamma^- + \Gamma^|)$, where $\Gamma^\pm$ is the width for these charged decay modes. In the Standard Model $\tilde{A}_{cb}$ is expected to be consistent with zero within our experimental uncertainty; a nonzero 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 $232 \times 10^6 \bar{B}B$ 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 $K/\pi$ separation of better than 4 standard deviations ($\sigma$) is achieved for momenta below 3 GeV/c, decreasing to 2.5$\sigma$ at the highest momenta in the $B$ decay final states. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter.

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

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

The upper (lower) sign denotes a decay accompanied by a $B^0$ ($\bar{B}^0$) tag, $\tau$ is the mean $B^0$ lifetime, $\Delta m_d$ is the mixing frequency, and the mistag parameters $w$ and $\Delta w$ are the average and difference, respectively, of the probabilities that a true $B^0$ ($\bar{B}^0$) meson is tagged as a $B^0$ ($\bar{B}^0$). The parameter $C$ measures direct CP violation. If $C = 0$, then $S = \sin2\beta + \Delta S$.

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 ($B_{flav}$).
We reconstruct a $B$ meson candidate by combining a $\pi^+ K^- \bar{p}_\mathrm{B}$ with an $\omega \rightarrow \pi^+ \pi^- \pi^0$. We select $K^0_S \rightarrow \pi^+ \pi^0$ decays by requiring the $\pi^+ \pi^- \pi^0$ invariant mass to be within 12 MeV of the nominal $K^0_S$ mass and by requiring a flight length greater than 3 times its error. We require the primary charged track to have a minimum of six Cherenkov photons in the DIRC. 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 $825 \text{ MeV}$. Distributions from the data and from MC with and without the hypothesis $\omega \rightarrow \pi^+ \pi^- \pi^0$ and of the $q\bar{q}$ candidate, respectively.

From MC simulations of $B^+ B^-$ and $B^+ B^-$ events, we find evidence for a small (0.5%) $\bar{B}B$ background contribution for the charged $B$ decays, so we have added a $\bar{B}B$ 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 $m_{\mathrm{ES}}, \Delta E, m_{3\pi}, \mathcal{H}$, and a Fisher discriminant $\mathcal{F}$ [13]. The Fisher discriminant combines five variables: the polar angles with respect to the beam axis in the $Y(4S)$ 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 $\Delta t$ for the $B^0 \rightarrow \omega K^0_S$ decay, while for the charged $B$ decays we use the PID variables $T_\pi$ 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 $B^0 \rightarrow \omega K^0_S$ decay we define the probability density function (PDF) for each event $i$, hypothesis $j$ (signal and $q\bar{q}$ background), and tagging category $c$.
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.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\omega \pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events in fit</td>
<td>44175</td>
</tr>
<tr>
<td>Signal yield</td>
<td>274 ± 28</td>
</tr>
<tr>
<td>Yield bias</td>
<td>18</td>
</tr>
<tr>
<td>Purity (%)</td>
<td>34</td>
</tr>
<tr>
<td>Eff. (ε, %)</td>
<td>21.8</td>
</tr>
<tr>
<td>$\sqrt{\prod B_i}$ (ε) (%)</td>
<td>0.891</td>
</tr>
<tr>
<td>$\epsilon \times \prod B_i$ (%)</td>
<td>18.2</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>10.8</td>
</tr>
<tr>
<td>$B(10^{-6})$</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>$\mathcal{A}_{ch}$</td>
<td>-0.01 ± 0.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\omega K^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events in fit</td>
<td>4145</td>
</tr>
<tr>
<td>Signal yield</td>
<td>266 ± 24</td>
</tr>
<tr>
<td>Yield bias</td>
<td>16</td>
</tr>
<tr>
<td>Purity (%)</td>
<td>46</td>
</tr>
<tr>
<td>Eff. (ε, %)</td>
<td>21.2</td>
</tr>
<tr>
<td>$\sqrt{\prod B_i}$ (ε) (%)</td>
<td>0.891</td>
</tr>
<tr>
<td>$\epsilon \times \prod B_i$ (%)</td>
<td>17.7</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>13.0</td>
</tr>
<tr>
<td>$B(10^{-6})$</td>
<td>6.1 ± 0.6</td>
</tr>
<tr>
<td>$\mathcal{A}_{ch}$</td>
<td>0.05 ± 0.09</td>
</tr>
</tbody>
</table>

Signal PDF parameters. In Table I we include estimates of these biases, evaluated by fitting simulated $q\bar{q}$ experiments drawn from the PDF into which we have embedded the expected number of signal and $B\bar{B}$ 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.

Figure 1 shows projections onto $m_{ES}$ and $\Delta E$ 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.

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 $\Delta t$ background shape. The parameters $\tau$ and $\Delta m_d$ are fixed to world-average values [15]. Here we find a slightly smaller yield of $95 \pm 14$ 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. Figure 2 shows the $\Delta t$ 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 $\leq 1$% in studies where the signal PDF parameters are varied within their estimated errors. The uncertainty due to $B\bar{B}$ background is also estimated to be 1% by variation of the fixed $B\bar{B}$ yield by its estimated uncertainty. The $\mathcal{A}_{ch}$ bias is estimated to be $-0.005 \pm 0.010$ 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 $B^+ \rightarrow \omega \pi^+$ and $B^+ \rightarrow \omega K^+$.

For the time-dependent measurements, we estimate systematic uncertainties in $S$ and $C$ due to $B\bar{B}$ background and PDF shape variation (0.01 each), modeling of the signal $\Delta t$
distribution (0.02), and interference between the CKM-suppressed $b \to u\bar{c}d$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tagside $B$ 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 $B_{\text{tag}}$ sample is used to determine the errors associated with the signal PDF parameters: $\Delta t$ resolutions, tagging efficiencies, and mistag rates; published measurements [15] are used for $\tau_B$ and $\Delta m_{d}$. 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 $\mathcal{B}(B^+ \to \omega \pi^+) = (6.1 \pm 0.7 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \to \omega K^+) = (6.1 \pm 0.6 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^0 \to \omega K^0) = (6.2 \pm 1.0 \pm 0.4) \times 10^{-6}$, $\mathcal{A}_{\text{ch}}(B^+ \to \omega \pi^+) = -0.01 \pm 0.10 \pm 0.01$, and $\mathcal{A}_{\text{ch}}(B^+ \to \omega K^+) = 0.05 \pm 0.09 \pm 0.01$, 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 2 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 $\sin 2\beta$ [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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[14] $f(x) \propto x\sqrt{1-x^2} \exp[-\xi(1-x^2)]$, with $x = m_{ES}/E_B$ and $\xi$ a parameter to be fit. See H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990).